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Reliable Metrics and Deployment Issues of Tactical ad-hoc Networks

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ABSTRACT

The mobile tactical network (MTN) utilized for wireless military communications networks are classified as MANETS. Modern tactical communication systems are highly heterogeneous dynamic networks interconnecting many different types of users. Involving personnel, vehicles, sensors, devices and other connected equipment, the users have vastly different communication requirements while co-existing in smaller or larger geographical proximity. Unlike their commercial counterparts, MTNs pose unique characteristics with restricted bandwidth. Thus, the commercial vendors of ICT equipment do not have sufficient experience or capabilities to deliver military grade products. Rather, modification of commercial product by the original providers or third-party vendors to meet the battlefield requirements is frequently common. Comprehensive comparison of the performance and design characteristics of the commercial MANETs and their military counterparts was carried out using NS2 simulations. It was found that for scenarios requiring long-range connectivity, hierarchical routing protocols give the most accurate performance predictions for MTNs. Further, it is necessary to consider the sizes of various military units, different topology area size, warfighting platforms and combat mission types. Finally, it is argued that many commercial off-the-shelf (COTS) technologies can be adopted for their use in MTNs, even though it requires a lot of additional efforts to overcome challenges not considered by the commercial solutions.

KEYWORDS: *COTS, MTNs, METREICS*

I. Introduction

In the past few decades, several commercial MANETs research projects have been conducted. These studies have used various metrics based on either 802.11 or short-range communications standards. However, the commercial use of large-scale MANETs appears to be non-existent. One reason is much easier deployment and management of systems with the dedicated infrastructure such as in cellular networks [1].

However, in some natural disasters or military operations the wired infrastructure can be damaged or not always applicable. Therefore, tactical MANETs are used extensively by military units with emphasis on security, range and integration with existing systems. These MANETs are enhanced by self-forming multi-hop capabilities to improve their flexibility and coverage, and to cope with a number of specific challenges in geographical areas. A major goal towards the MTNs evolution is to provide accurate, valuable and timely information for many different types of users with heterogeneous communications and computing requirements such as in the current C4ISR systems [2]. The users are represented by sensors, surveillance satellites, unmanned aerial vehicles (UAVs), airborne platforms, vehicles, and ground troops. The MTNs, however, very different from generic MANETs. For example, The MTNs are typically operated with restricted bandwidth in very high and ultra-high frequency bands (UHF and VHF) with different propagation loss properties [3]. The understanding of networks properties is important to effectively evaluate networking solution options pragmatically. On the other hand, security is a main concern in the establishment of MTNs. Mobile nodes are deployed in unsafe, unpredictable hostile environments makes the networks susceptible to a combination of possible attacks [4].

The currently available COTS technologies are major drivers of military communications needs. Recently, various military systems continue to adapt commercial technologies to military applications such as satellites, smart devices and sensors. However, the limitations to commercial COTS products adoption primarily arise due to the special requirements of soldiers at the tactical edge. The purpose of this paper is thus to investigate the differences between military and commercial applications of MANETs including the requirements for communications services, network topology, and the performance metrics. The study focuses on the deployment and operation of MTNs at the tactical edge of the battlefield theatre. A corresponding framework is created to support decisions on what technologies and solutions should be included in future generations of MTNs. The contents of the next sections are as follows. The effective adoption of commercial information and communication technologies (ICT) at the tactical edge of the battlefield is discussed in Section II. The main characteristics of MTNs such as the heterogeneity and the properties of physical radio links are investigated described in Section III and IV, respectively. The effect of protocol type and operation area size in MTNs are examined in Section V including realistic modeling of nodes mobility and radio wave propagation conditions. Conclusions are given in Section VI.

II. The Integration of COTS Radios into MTNs

The recent advances in ICT also strongly impact the design of MTNs, especially at the tactical edge. The ICT reduce the time to deployment, provide advanced abilities and reduce the operational cost of MTNs. The COST products provide new opportunities for their use in the military domain which did not exist previously [5]. We can consider at least two perspectives to compare COTS based MANETs and their military counterparts.

From the technology perspective, the COTS solutions that may be useful in tactical scenarios are cognitive radio (CR) networks, software defined (SDR) networks, and autonomous networks [6]. Many tactical networks rely extensively on existing public protocols particularly at the network and transport layers [7], and use the Internet protocol (IP) including IPV6 version for traffic backhaul [8]. The Global Information Grid (GIG) is the main infrastructure and enterprise solution for tactical communications developed by the Department of Defence (DOD). It employs a mixture of many military proprietary and public COTS technologies. However, most military users consider the use of public COTS technologies to present a severe security threat, since the 3rd parties may have accurate knowledge of the functioning and structure of some internal components and subsystems. Using the COTS security solutions in MTNs is often challenging of even undesirable [9].

From the economic perspective, the economies of scale are vital for offering affordable commercial products. This is more difficult to achieve for the military products, even though the demand for cyber security solutions, navigation systems and UAVs has increased significantly in recent years. The defence manufacturers are now focusing on advancing the lightweight electronics, small antennas, and other radio frequency (RF) technologies. The COTS hardware and software is finding its way to the Internet of Things (IoT) in the military C4ISR structures [10] . Since the level of financial support determines the achievable capabilities and performance of technology, it is likely the commercial drivers will influence the development of military networks much more in near future than ever before.

A. *Technology challenges at the tactical edge*

The conditions encountered by the MTNs are vastly different from those assumed in the deployment of commercial ICT products. Hence, the military sector has a long history of developing its bespoke technological solutions. The cost benefits of COTS solutions together with careful planning create new opportunities to use these technologies in military applications. However, the cheap solutions may entail the security and robustness concerns. One has to also consider typical radio communication trade-offs between the capacity, range and data rates. In order to serve much higher demands for data rates, the newer MTNs are primarily using the larger bandwidth between 4.4 to 5.4 GHz under more line-of-sight (LOS) conditions whereas the legacy MTNs were designed for the 1350-2690 MHz frequency band and BLOS transmissions. Overall, the challenges in using COTS solutions in military communications can be summarized as follows [11]:

1) Insufficient support of mobility to the degree encountered in MTNs.

2) Commercial pressures for short development cycles leading to frequent technology updates is undesirable in military applications.

3) The market dynamics for military products and the resulting returns on investment are very different from the commercial sector.

4) The commercial vendors of ICT equipment do not have sufficient experience or capabilities to deliver military grade products, for example, to guarantee the quality of service (QoS) over wide range of operating and often quite adverse conditions.

5) The cost efficiency of COTS solutions may be completely offset by lack of reliability and performance guarantees in realistic military environments.

B. Unique technological requirements

The barriers to adoption of commercial ICT in the military context primarily arise due to unique requirements at the tactical edge and involve the policy, environmental and technical considerations including, but not limited to, the robustness of service provisioning and information assurance. In addition, the MTNs have significantly stringent security requirements than the commercial MANETs. Therefore, a direct adoption of COTS technologies without adjustment is not recommended [12]. In some applications, the constraints of the original COTS design can be accepted, for example, the commercial-grade radios can operate successfully provided that the mobility of nodes in MTNs is limited even though the full spectrum management may be problematic [13]. It is useful to recognize that the latest function-rich COTS technologies may be less suitable for use in military systems, and that their adoption may still requires significant purpose-driven research and further development [14].

III. Exploitation of MTNs Heterogeneity

The overall goal for research on heterogeneous networks is "To enable defense users to reliably obtain and share necessary and timely information in the right form over an integrated heterogeneous dynamic network which is scalable and evolvable" [15]. More so than the civilian sector, the absence of an integrated architecture in the past decades was among the leading causes of MTNs heterogeneity. Several deployed communications systems operate, particularly during the conduct of combat. In military tactics, army, air forces, navy, and special units cooperate to obtain specific tactical targets. Different domains employ different types of devices, network structure, offered services and security policies. The ability to provide seamless and adaptive service delivery processes in such a heterogeneous environment is key to the success of next-generation tactical MANETs [16]. In fact, most recent researches have focused on the communication interoperability to capture heterogeneity-enabling technologies. On the other hand, the desire for individual soldiers to always be connected has continued to grow as the underlying technology improves. To accommodate this desire, the Heterogeneous Networks (HetNets) ultimately will become the norm for MTNs as it is for strategic networks and in the Internet.

A. Heterogeneous structure of tactical networking environment.

The next-generation MTNs are evolving into very complex heterogeneous networks in terms of architecture, protocols and security. On the other hand, the systems combine a variety of different transmission technologies (capacity, range, delay, etc.). At a higher level, heterogeneity may also refer to different network policies as well as trust and security management [16]. However, tactical networking structure can be broken into three IT environments. Each of these environments represents a specific group of mission functions. However, all levels together form the multiple operating system environments that need to accomplish assigned tasks. These core types of networks are Strategic level, Tactical deployed lev1e and Tactical mobile level (MTNs) [17]. The heterogeneity problem became more obvious due to variety of technologies, functionality, telecommunications equipment or even nodes mobility at each level. At the highest level, the strategic backbone network with fixed infrastructure provides the high speed and high bandwidth solutions. At the task force, the deployable tactical network with primarily stationary network or satellite system are designed to becoming semi-mobile and adaptable to future missions. At the individual soldier, the high mobility MTNs are characterized by low bandwidth, variable throughput and unreliable connectivity. Therefore, the heterogeneity of tactical scenarios calls for adaptive communication systems that allowing a transparent network for tactical environments, where warfighters can communicate end-to-end without technology boundaries.

B. Next-Generation architectures solutions for heterogeneity

The MTNs Advancements for the next generation requires significant improvements to provide greater flexibility and increased interoperability. Services such multimedia content delivery, Blue Force Tracking (BFT) and remote control of sensors will shape tomorrow's digital battlefield environment [18]. Due to the increasing heterogeneity at all levels within military organization, the adoption of software/hardware architecture principles is becoming essential. However, these mechanisms and solutions for the mobile tactical edge must interact very well to meet future Joint Communication requirements. For instance, Joint Tactical Radio System (JTRS) pursued to replace current military MANETs in the USA army with a single set of SDR that can function as multiple radio types and upgrade radio systems with ease. it should be clear that these concepts can enable a broad range of possible outcomes such as ease of spectrum congestion network resources management and dynamic spectrum access for fast network deployment without compromising security [19]. However, the demand will be met by a combination of both tactical and commercial wireless communications techniques. Today gateways or other interconnection techniques are engineered to support tighter integration in large-scale heterogeneous networks [20]. However, the need to increase the reachability and data rate of a wireless network in a tactical environment require the development of new constructs for future network and communication architecture. Instead of using traditional hardware components, an efficient Reconfigurable Radio Systems (RRS) becomes more essential, so that several different ICT systems can be connected. However, table 1 presents a general overview of emerging technologies that need to face and shape the future combat systems [21].

Table 1: *Future trends of tactical heterogeneous solutions*

Novel technologies	Heterogeneity solutions
Reconfigurable Radio Systems (RRS)	• Loading the essential waveform and signalling specifications in software. • All technologies for RRS mainly consist of two parts (SDN and CR)
Software Define Networks (SDN)	• The functionality of hardware components provided in software running on a computer or in an embedded system. • Enable the operator to single out the most suitable radio waveform that provide a flexible, widely-applicable solutions for different operating environments
Cognitive Radio (CR)	• Allows intelligent dynamic spectrum allocation to give improved spectral utilization. • Intelligently monitor and analyse its operational radio environment, to decide which frequencies and channels are in use and which are not • Adjust its operational parameters to choose the most appropriate protocols and frequencies for data transmission over wireless channel

Network Functions Virtualization (NFV)	• Decouple network functions from dedicated hardware devices (virtualize), deploy and manage the network service, then • Allow these services to be hosted on virtual machines (VMs). • Build a service chain with less dedicated hardware devices.
IP-based networking	• Enhance connectivity, throughput and backbone network performance with more flexible network configurations. • Offers the prospect of ubiquitous real-time data sharing across different levels of commands and theatre of operations

IV. Physical- Layer Modeling

Physical radio link properties are the characteristics associated with the physical link. The tactical network is, however, very different from generic MANETs. For example, the protocols for MTNs must be tested for highly dynamic topology changes under connectivity characteristics observed in realistic terrains and environments. In practice, the field-tests are time-consuming, costly, and they may not be up to scale. Thus, it is crucial to appoint realistic radio models to investigate performance metrics studies and to gain trust and confidence in the designed MTN. Selecting the appropriate stimulation parameters would underestimate the real performance in the same way as they are implemented on real systems [22]. However, the main models that has a strong impact on the results of the simulation are the movement of the network nodes and the radio wave propagation [23]. This section discusses why most of the mobility models and radio propagation model used in today's commercial MANET simulations are unsuitable to give a good approximation of a military tactical MANET environment.

A. Realistic mobility models of Multi-hop MTNs.

A mobility model plays an important role for evaluation algorithms in MANET. Moreover, the type of movement pattern has a straight effect on the length of the path, link constancy, and size of neighbors for each mobile user. It also intended to capture the routes position, speed, and acceleration change over time. However, there are numerous mobility models [24]. A frequently used Random Waypoint (RWP) for MANET simulations provides the worst-case scenario for protocols performance. in contrast, the movement patterns that their architecture depend on groups/clusters are one of the worst-case scenarios in urban situations [25]. Generally, Simple models draw wrong conclusions of required services the upper layers [26]. The MANET nodes in the commercial applications usually moves in less coordinated way, so the random mobility models are more appropriate in these situations. In contrast, military communications systems tend to require unique solutions. Importantly, in military scenarios, the node movements are influenced by the headquarters or by a mission commander as well as by the tactical goals of the mission. The nodes need to closely collaborate, so their movements are highly correlated. It leads to formation of the mobility groups which are following the mission leader. There is also heterogeneous velocity based on the type of node for either vehicles or pedestrians. In such scenarios where the swarming phenomenon occurs, the group-based mobility model such as Reference Point Group Mobility (RPGM) and Reference Region Group Mobility (RRGM) RPGM model best describes the node movements. However, the provisioning of security in MTNs is more challenging due to nodes mobility and the distributed nature of soldiers make these networks more prone to jamming and eavesdropping.

B. Realistic Radio Propagation Models of MTNs.

Another key factor significantly affecting the performance is the choice of the radio propagation model. In fact, it is considered as the most significant factor used as the physical layer models to obtain more accurate and meaningful results [27]. Provided that we assume a radio propagation model that does not accurately describe the realistic propagation conditions, it can either underestimate or overestimate the system performance. The two most important parameters in radio propagation model are the carrier frequency and the transmission distance between the transmitting and receiving antennas. In theory, it used to estimate the transmission power and path loss between nodes for determine the ideal transmission distance. Numerous common numerical models have been developed in the literature with different degrees of complexity and accuracy [28]. In commercial MANETs, network developers commonly offer simple radio that neglect obstacles of the network performance. In the case of tactical MANETs, the mobile propagation paths suffer from several external environmental factors. It is difficult to define a single model that can predict all behaviors of propagation wave. Thus, understanding the effects of varying conditions and awareness of operating area is of vital importance to design mobile LOS tactical network solutions. During the simulation run, tactical planners can evaluate situations and predict of any possible problems that may appear during a real mission. In general, waves that travel through varied terrain and harshest conditions can be described with reflection, diffraction and scattering. Therefore, Two-ray ground propagation model shows better results with varying transmitted power and number of nodes as compared to free space propagation model that using the theory of spreading electromagnetic waves in an ideal vacuum. Moreover, tactical Antenna is a key element in a communication system to suit all operational requirements. However, this model takes advantages from the physical height of antennas with or without mask [29].

V. Peformance Comparison

NS-2 is used as a simulation tool to evaluate and compare the performance of the of MTN architectures.

Comparison Metrics

Four metrics are used to compare the performance of MTNs and MANETs. Here, we assume the following network metrics:

1) Packet delivery ratio: is the average of number of successfully packets received at the soldiers to the total number of packets sent in the network.

2) Routing overhead: to find routes, routing protocols used to send control information (packets).

3) Average throughput: is the ratio of successfully received bits over time needed to transport the bits.

4) End-to-end delay: is the time for packet to reach the destination after leaving the source

Network deployment scenario

The current MTNs involve between 20 to 60 nodes which may scale up to 200 nodes in the future designs. The MTNs usually operate in the field of the size, say, 10 by 10 km. The nodes are divided into several groups, and each group has its group leader. One of the group leaders also serves as the main leader of all other groups. The nodes are uniformly distributed about their group leaders who are following the main leader by maintaining a constant distance and the same direction. This yields a mobility pattern that is best described by the reference point group mobility model [30]. The nodes travel at speeds 30-80 km/h, and the mobility is interleaved with pauses of up to 30 min in duration.

Simulation Results and Discussion

In this subsection, the performance of MTNs is evaluated

and compared with conventional MANETs. Our simulations assume realistic mobility and radio wave propagation models, as well as the multi-hop capabilities of MTNs. The simulation parameter has shown in Table 2.

Table 2: **Simulation Parameters**

Object	Parameter	Value
Network node	Medium RF propagation MAC Antenna Routing protocol Number of nodes Packet size Mobility	Wireless channel two-ray ground models 802.11 Omni-directional AODV-HAODV 25-250 512 bytes RWP, RPGM, Manhattan
Network scenario	Simulation time Simulation area size Pause time Speed Transmit power	1000 sec 10 km × 10 km 1 km × 1 km 30 sec 80 km/h 46 dBm for vehicles and 30 dBm for patrols

The RPGM and two-ray propagation model describes the physical layer modeling in MTNs more accurately and therefore they are used in this paper. Next, we numerically compare the responses of commercial MANETs and MTNs assuming different protocol type. In this scenario we change the number of nodes. The packet delivery ratio rate for commercial MANETs and MTNs are shown Fig 1. We observe that the HAODV model yields the best performance, and it outperforms the flat AODV protocol considered by 68% on average. In large network, the network can be broken down into a hierarchy of smaller networks, where each level is responsible for its own routing, so cluster-based approaches perform better than flat ones. The average throughput and the average delay for the same set of experiments are then shown in Fig. 2 and Fig. 3, respectively. We can again observe that AODV protocol underestimate the performance of MTNs compared to the performance of more realistic HAODV protocol. The performance bias of different routing protocols is also observed when considering the routing overheads as shown in Fig. 4. The minimum improvement in routing overhead for the HAODV occurred at 25 mobile nodes at which the overhead is decreased by 1.3 compared to AODV, while the maximum improvement occurred at 50 mobile nodes at which the ratio is decreased by 68.9 compared to AODV. On the average, we can realize that the HAODV always outperforms AODV related to minimizing routing overhead at different network densities by 50.8. The key point of H-AODV is that routing scheme can take advantage of hierarchical structure to improve the protocol scalability for large-scale heterogeneous networks.

Military scenarios may be classified by their geographical coverage and the size of the mission. Further, major challenges in MANETs which becomes more difficult when the network size increases. Therefore, the network size is one of the major parameters in simulation studies of routing protocol evaluation in MANET. At the same time, the movement pattern of warfighters can reduce the impact of network area size on the performance of ad hoc routing protocols. Therefore, this study was designed to examine the influence of different kinds of mobility models with varying network size on above-mentioned performance metrics. We consider the following MANET mobility models: RPGM, Random Waypoint (RWP) and Manhattan mobility models. The simulation experimental study has been performed for two different network area sizes of (1000 x 1000 m) and (10000 x 10000 m). This scenario is simulated for 250 number of mobile nodes and two-ray ground model is used for radio propagation model. However, packet delivery ratio at different topology areas size of different mobility models is depicted in Fig. 5. We observe that, the overall performance of the network decreased when the area size is increased. In case of RPGM mobility model the packet delivery ratio decreased by 32% compared in area 1000 m^2. In contrast, RWP and Manhattan mobility model, the performance is very bad when the area size increased, the packet delivery ratio decreased by 64.6% and 74.8% respectively. However, it can be concluded that, the RPGM always outperforms at different operation area size. Fig. 6 compares the average delay and Fig. 7 shows the average throughput results, respectively, for the two simulation area size considered. We observe that, on average, RPGM always outperforms the RWP and Manhattan mobility. In Fig. 8, it has been shown that RPGM is more effective to reduce the route overhead when compared with existing mobility models by 27.4 and 81.4 respectively. Thus, this model is well suited for large operations area with significant barriers to communication (e.g., mountains, oceans, and cities)[14].

VI. Conclusions

When considering the implementation of MANETs in the tactical space for military applications, it is essential to consider the type of transceivers and communication platforms deployed as well as the application requirements. The unique attributes of MTNs including the specific environment characteristics and deployment scenarios as discussed in this paper have a significant impact on the adoption of MANETs for military use. Thus, assuming generic MANET solutions for the use in military applications can be very misleading in achieving trustable and reliable military grade MTNs.

Despite a vast progress in commercial technologies including ICT, the COTS solutions need to be adapted to the military needs by continuing focused research efforts. The research and development towards enhanced capabilities of MTNs is only as good as the accuracy of the underlying physical models considered, especially considering the mobility and radio propagation models. The MTNs are more demanding to use (often proprietary) protocols to support multi-hop self-forming and self-healing features. Moreover, it is critical to consider the security threats which are often of different nature than in the civilian cyber networks. As the ICT are getting more complex while also becoming the critical part of the communications infrastructures, the use of hardware and software COTS solutions poses severe security risks. The security testing of complex hardware and software components from the 3rd party developers and suppliers is an open and challenging research problem.

Our numerical results confirm the importance of choosing the right models to evaluate the performance of MTNs in order to capture the realistic dynamics of these military networks. We argued that the RGPM model for node mobility and the two-ray model for radio propagation are the most realistic choices to describe the deployment and operation of MTNs. Further investigation was also carried out on the impact of flat protocols and hierarchical routing protocols. The main thrust of the study is to identify a potential hierarchical routing algorithms that much more appropriate for a tactical heterogeneous MANET topology. Such behavior was observed generally for all the performance metrics considered. The last numerical results in the paper illustrate the influence of different operation area sizes on network performance under different mobility patterns. The result shows that how environmental parameters such as the size of operation play central role to determine the network properties that are more accurate, especially in large operations area, such as disaster area recovery, urban warfare and reconnaissance. Also, the increase in area size can have a significant impact on network performance and reliability. High network density can improve the network performance in terms of reliability and robustness. However, it caused many challenges in the design management of military MANETs. Finally, the outcomes are very useful to present the importance of using realistic simulation environment in order to compare and assess the performance of different technologies used in the tactical network.

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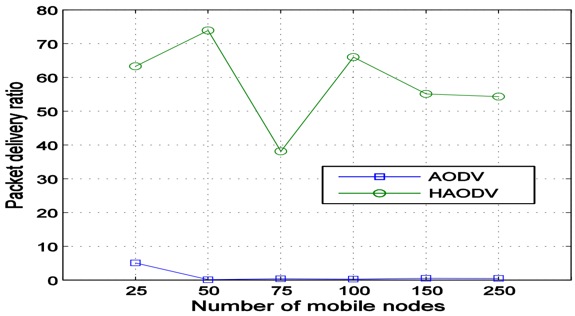

Figure 1: Packet delivery ratio under different network density

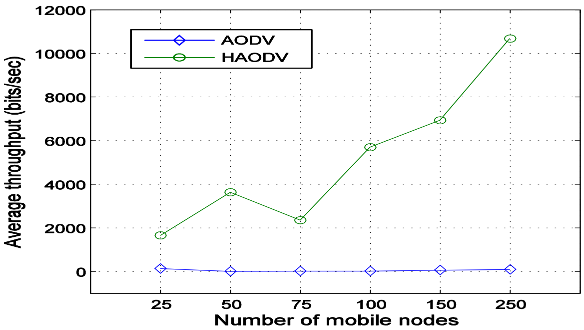

Figure 2: Average throughput under different network density

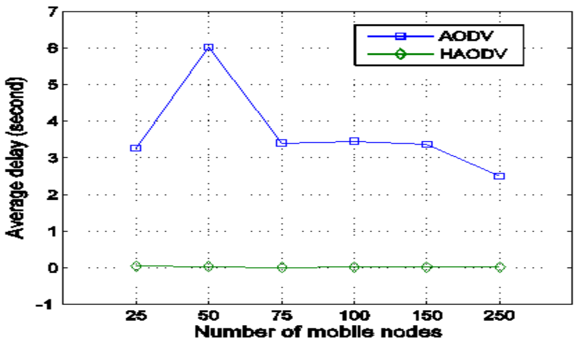

Figure 3 : Average delay under different network density

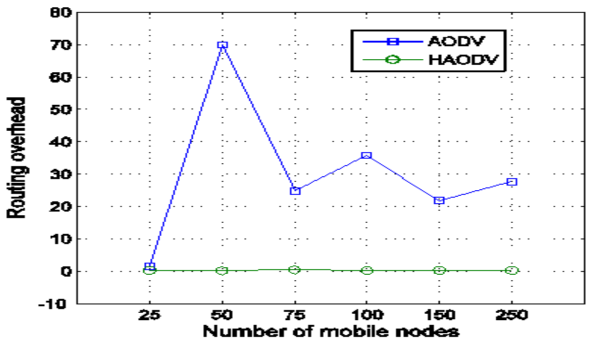

Figure 4 : Routing overhead under different network density

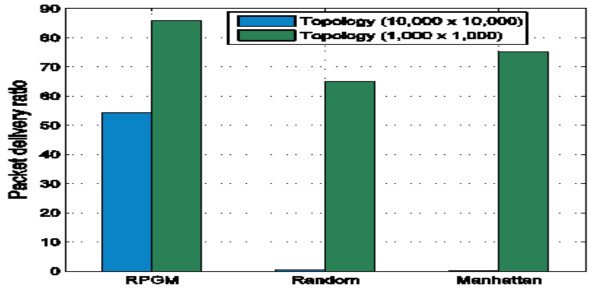

Figure 5: Packet delivery ratio under different topology area

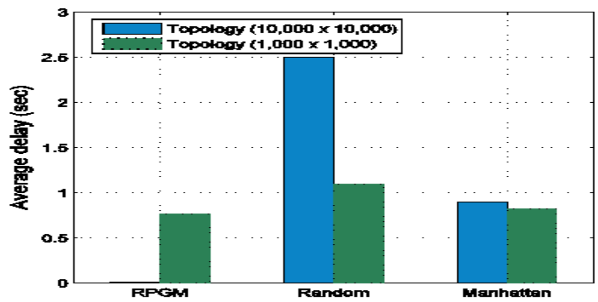

Figure 6: Average delay under different topology area

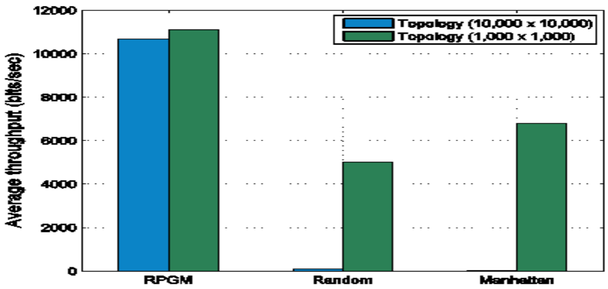

Figure 7: Average throughput under different topology area

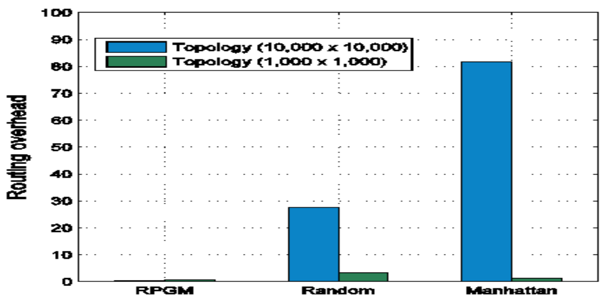

Figure 8: Routing overhead under different topology area