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A Comprehensive Survey on Multi-hop Wireless Networks: Milestones, Changing Trends and Concomitant Challenges

Gaurav Khanna[1] · **S. K. Chaturvedi**[1]

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Abstract With remarkable advancements in the fields of global satellite based navigation systems and wireless communication networks, there is a tremendous increase in the number of mobile device users throughout the globe. Each day, new arduous projects and applications utilizing mobile devices are evolving, with a prime motive to deploy wireless multi-hop networks into the real world. As these networks are, in general, deployed in extreme environmental conditions their performance evaluation is a matter of great concern and demands rigorous analysis. Several models, simulators, testbeds and visualization tools have evolved in the last two decades for analyzing the characteristics of these wireless multi-hop networks. In this paper, first we discuss a number of models and the changing trends of research along with the associated challenges. Then, we discuss several simulators, emulators, testbeds and real world projects implementing such networks. Besides, we also discuss an important aspect of wireless multi-hop networks, i.e., reliability and identify various imperative metrics from the literature for performance evaluation of such dynamic networks.

Keywords Mobile ad hoc networks · Network models · Network performance metrics · Network reliability · Network simulators · Time varying graphs

✉ Gaurav Khanna
gauravkhanna@iitkgp.ac.in

S. K. Chaturvedi
skcrec@hijli.iitkgp.ernet.in
https://scholar.google.co.in/citations?user=ULGIT6UAAAAJ&hl=en

[1] Subir Chowdhury School of Quality and Reliability, Indian Institute of Technology Kharagpur, Kharagpur, India

1 Introduction

In the last decade, a plethora of research papers have been published in the field of multi-hop wireless networks *viz*., mobile ad hoc networks (MANETs) and alike, with a primary objective to study the various aspects of these networks like application oriented development, complexity reduction, realistic simulation models, development of real network testbeds, mobility modeling, trace collection, link existence modeling, routing, reliability, clustering and information diffusion, transmission range and many more. Despite, being in so much of demand, ad hoc networks pose a great challenge to the researchers for their performance evaluation. The primary reasons behind such a challenging situation could be attributed to the harsh and disruptive environment of applications, mobility of nodes, interference and energy constraints.

In general, MANETs are self-configuring, dynamically changing, multi-hop, and infrastructure-less networks, wherein each node can act as a host as well as a relay by passing the data packets to the nodes in its vicinity. In the beginning, MANETs found applications mainly in defense, disaster recovery and distributed collaborative computing; but, in recent years, due to advancements in wireless technology, ad hoc networks can easily be spotted in many public and office environments, where they usually compliment the pre-existing infrastructure-based communication networks. Besides, recently several "MANET-born" communication network paradigms, namely, mesh, sensor, opportunistic mobile networks (OMNs), delay tolerant networks (DTNs), vehicular ad hoc networks (VANETs), flying ad hoc networks (FANETs) and people-centric networking, have also become very successful and widespread [1].

In MANETs, dynamically changing network topology leads to the formation of new links and/or breaking of existing ones. This phenomenon also changes the data routes among the communicating nodes. The situation becomes even more dynamic in highly mobile networks like FANETs, VANETs and DTNs/OMNs, as these networks either have frequently changing end-to-end connectivity or depend on *store and forward* mechanism to transfer data packets. Hence, with the increasing dependency of many applications on wireless modes, there seems to be an ever growing demand for more reliable wireless networks. Looking at the versatility and utility of these networks, there has also been tremendous efforts to resolve the issues such as mobility patterns, energy management, self-configuration, routing, reliability, quality of service provisioning, scalability, link reliability models, and cost-effectiveness etc., that affect the design, deployment, and performance of an ad hoc network. But, many other aspects of such dynamic and complex networks continue to pose challenging situations during their implementation and performance evaluation.

The Literature indicates that almost every study on MANETs is carried out with the help of either analytical modeling, using simulators/emulators or by real world experiments (Fig. 1). Each of these approach has its advantages and limitations as well. Through this survey, our main aim is to summarize the current *state-of-the-art* developments in the area of wireless ad hoc networks, and highlight the changing trends and challenges involved in the design and implementation of these ad hoc networks.

Consequently, here we congregate bits of work into a well-arranged survey focusing on the comprehensive review of various models available in the literature for studying different aspects of wireless ad hoc networks, accompanied with various tools for studying mobility of human beings and vehicular traffic. Furthermore, we provide details on the Satellite Navigation Systems (SNS) along with their strengths, limitations & applications, and existing data repositories. We provide an insight into the trends of research focus and

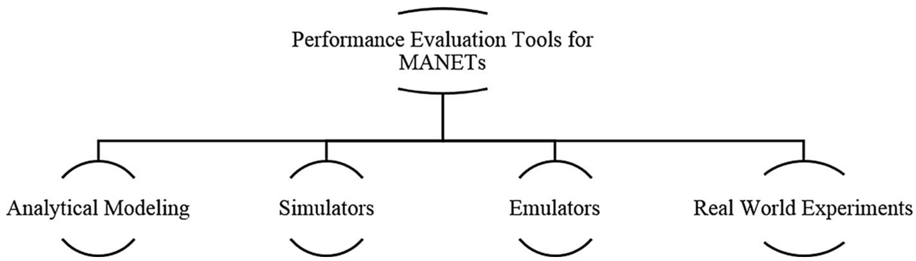

Fig. 1 Performance evaluation tools for MANETs

discuss various simulators, emulators and testbeds along with their specific features. We also collate several worth mentioning real projects (completed or ongoing) throughout the world to address various challenges in their implementation in disruptive environments. Besides, an important aspect of every network, i.e., reliability and various performance metrics have also been outlined along with various challenges for future research. In general, this survey aims to fill the existing gaps in the literature, which originate (in our opinion) due to the ever expanding nature of the domain with the updated information.

The remaining paper is organized as follows: In Sect. 2, we present various techniques for modeling MANETs. In Sect. 3, we discuss the changing research focus from MANETs to MANET-born networks. In Sect. 4, we have covered a number of simulators, emulators and testbeds designed for studying MANET and alike networks. Section 5 presents a number of real world projects initiated throughout the world with a motive to develop new Information and Communication Technology (ICT) based applications. In Sect. 6, we discuss the reliability evaluation related challenges and available solutions in MANETs. Section 7, presents some future prospects of the domain. Finally, some concluding remarks of this review are presented in Sect. 8.

2 Modeling MANETs

A number of models have been proposed in the literature to study/predict performance characteristic(s) of MANETs. This section details some key models as hereunder.

2.1 Mobility Modeling

MANET mobility is one of its key attributes as the complex mobility patterns of nodes require more parameters and assumptions to be included in the constructed model. Moreover, complex mobility also greatly influences the networking protocols, application services, and reliability of the network. Thus, the impact of mobility should be known in advance for a better design and implementation of MANETs. In the following paragraph, we discuss the two major categories of mobility models i.e., synthetic mobility models and trace based mobility models; where, a synthetic mobility model depicts randomly generated movements and creates synthetic traces while a trace-based mobility model is developed by monitoring and extracting the features from the real movement patterns of users carrying mobile nodes.

2.1.1 Synthetic Mobility Modeling

A number of synthetic mobility models have gradually been evolved for various applications [2–7]. The most frequently used models to study the impact of the mobility of nodes in MANETs are: Random Way Point Model (RWPM), Random Direction Model (RDM) and Gauss Markovian Model (GMM) [8, 9]. The node mobility of MANET causes the network topology to change with time and therefore a network's performance must be dynamically readjusted to such changes. Further, it should be borne in mind that it is very difficult to emulate real-life mobility pattern owing to its tremendous complexity, which depends upon several dependent/independent factors such as: (a) the terrain of movement, (b) traffic pattern over the network, (c) human behavior and (d) mission objectives. For a recent review on exhaustive taxonomy of mobility models, one can refer [10].

The role of mobility modeling in studying characteristic properties and performance of MANETs appears to be understood by now. A number of simulation tools to mimic the node movement are now available that can generate and analyze the impact of human or vehicle mobility under various traffic scenarios, and have widely been used by researchers, consultants and government agencies for some specific applications. Table 1, summarizes the various mobility simulation tools that have evolved over a period of time and proven to be of great help to researchers, scientists, government agencies or consultants along with various mobility models supported by them. For each tool, a pointer to their availability information is also provided.

2.1.2 Trace Based Mobility Modeling

Although many synthetic mobility models have been proposed and utilized by researchers, yet, most of them fail to reflect the real movement of nodes. In order to obtain realistic mobility patterns, researchers are devising new methods to harness data from real scenarios with the help of satellite navigation services (SNS). The data obtained from a real scenario is called a *trace*. A thorough study of the individual movements can successfully be accomplished with the help of mobility traces. The mobility traces with actual geographical coordinates in terms of *latitude*, *longitude* and *time-stamps* collected with the help of Global Positioning System (GPS) device create more real movement pattern of human beings or vehicles. The Pros and Cons, and challenges of both synthetic and trace based mobility models have been collated in Table 2.

In the following discussion, we present the SNS operating or under development phase throughout the globe along with their salient features.

1. *Satellite navigation systems and their importance in location prediction and trace collection*

   The United Nation's satellite navigation system i.e., *Navigation Satellite Timing and Ranging Global Positioning System*, commonly known as NAVSTAR GPS or simply GPS was primarily fabricated for assisting defense personnel and military planners in targeting enemy troops, fleet management, positioning, and navigation. Later, this service was freely made available to the civilians throughout the globe for numerous applications including tracking package delivery, mobile commerce, emergency response, exploration, surveying, law enforcement, recreation, wildlife tracking, search and rescue, roadside assistance, stolen vehicle recovery, satellite data processing, and resource management [26]. The importance of GPS became evident very soon and countries like Russia and European Union started developing their own

Table 1 Tools for mobility modeling

S. no.	Tools	Brief description	Type	Model simulation capability
1.	BonnMotion [11]	A Java based mobility scenario generation and analysis tool. The generated mobility scenarios may also be exported in wireless network simulators like ns-2, GloMoSim, or QualNet	Free	Random-Waypoint, Random-Walk, Gauss-Markov, Manhattan-Grid, Reference-Point-Group, Disaster Area, Random-Street
2.	CanuMobiSim [12]	It is a flexible framework for user mobility modeling. It can simulate spatial environment, user trip sequences, and user movement dynamics with the meta-mobility models and vehicular dynamics	Free	Random-Waypoint, Brownian-Motion, Meta-Mobility
3.	CORSIM/TSIS [13]	Software tool for simulating traffic on surface streets, freeways, and integrated networks. It is a combination of two traffic simulation models, NETSIM for surface streets, and FRESIM for freeways	Commercial	Vehicle and driver behavior
4.	HUMsim [14]	A generator of realistic, synthetic trace of human mobility	–	Behavioral
5.	IMPORTANT [15]	A framework to understand and analyze the impact of mobility pattern on routing performance of MANETs	–	Random-Waypoint, Reference-Point -Group, Freeway, Manhattan-Grid
6.	MobiSim [16, 17]	A simulator for performance evaluation of various network routing protocols in MANETs	Free	Random-Waypoint, Reference-Point -Group, Gauss-Markov, Random-Walk, Freeway, Manhattan-Grid
7.	PTV Vissim [18]	A powerful tool for the evaluation and planning of urban and extra-urban transport infrastructure with capability to simulate various traffic patterns originating from motorized private transport, goods transport, rail and road related public transport, pedestrians and cyclists	Commercial	Realistic motion model of all road users
8.	Quadstone Paramics [19]	It is a leading simulator for traffic simulation and transportation infrastructure planning. It can simulate both pedestrian and vehicular traffic and is powerful enough to model an entire city's traffic system	Commercial	Pedestrian and Vehicular traffic

Table 1 continued

S. no.	Tools	Brief description	Type	Model simulation capability
9.	SUMO [20]	Allows simulation and modelling of inter modal traffic systems. It can be used in route finding, visualization, and network import and emission calculation	Free and open source	Pedestrian and Vehicular traffic
10.	Toilers-Code-Base [21]	It is a rich collection of a number of published works along with associated codes for the models and services developed thereby	Available on demand	Random-Waypoint, Random-Walk, Reference-Point-Group, Gauss-Markov, Random-Direction
11.	TraNS [22, 23]	A GUI tool that integrates traffic and network simulators (SUMO and ns-2) to generate realistic simulations of VANETs	Open source	Vehicular traffic
12.	TRANSIMS [24]	An integrated system of travel forecasting tools for planning transport systems and emissions analysis	Free and open source	Transport system
13.	VanetMobiSim [25]	It is an upgraded tool similar to CanuMobiSim. It supports new realistic automotive mobility models for studying and understanding, car-to-car and car-to-infrastructure interactions	Free	New realistic automotive mobility models

CanuMobiSim CANU Mobility Simulation Environment, *CORSIM/TSIS* Corridor Simulation/Traffic Software Integrated System, *HUMsim* Human Urban Mobility Simulator, *IMPORTANT* Impact of Mobility on the Performance of RouTing protocols in Adhoc NeTworks, *SUMO* Simulation of Urban MObility, *TraNS* Traffic and Network Simulation Environment, *TRANSIMS* TRansportation ANalysis and SIMulation System

SNS. Today, there are a number of SNS under operation or underway worldwide. These SNS provide either regional positioning or global positioning just like NAVSTAR GPS. Table 3, provides a brief description of such SNS.

Presently, the United Nation's GPS is the most famous positioning service worldwide for its ability to provide global, precise and continuous three-dimensional position and velocity information along with Coordinated Universal Time (UTC) to the users with the appropriate receiving equipment [33]. The names of few renowned GPS receiver manufacturers are: *Avidyne*, *CMC Electronics*, *GARMIN*, *Honeywell*, *Rockwell Collins*, and *Universal Avionics*.

Fundamentally, the GPS satellite constellation consists of at least 24 satellites (plus some spares) arranged in 6 orbital planes with 4 satellites per plane. Moreover, at present GPS has a total of 32 satellites deployed in space. GPS mainly relies on trilateration or triangulation techniques for positioning in three dimensions (latitude, longitude, and elevation) and requires that at least four satellites are above the horizon. The accuracy of the geographical coordinates depends on the number of such satellites and their positions [34].

Table 2 Pros and Cons, and open challenges of synthetic and trace based mobility models

S. no.	Category	Pros and Cons	Challenges to handle
1.	Synthetic models	1. Usually fails to perfectly represent real life mobility 2. Low deployment cost 3. High computation overhead 4. Scalable and can be applied to an arbitrary number of nodes 5. High complexity 6. Plethora of models are available	1. Difficult to design a widely acceptable-realistic and simple mobility model 2. Hard to decide a suitable model for a given scenario 3. Difficulty in validation via traces 4. Speed decay problem 5. Extremely variable values for the parameters of simulations
2.	Trace based models	1. Represents real mobility 2. High deployment cost 3. Low computation overhead 4. Not Scalable 5. Low complexity 6. There is scarcity of real world traces	1. Huge variation in collected trace data with respect to day and time 2. Missing Data 3. Requires filtering and pre-processing 4. Sufficient samples nee to be acquired

Table 3 List of SNS operational/underway throughout the world

S. no.	SNS name	Proprietor	Coverage	Total number of satellites	Status
1	BDS [27]	China	Regional (Global expansion in progress)	35 (5 in Geostationary orbit and 30 in Non-Geostationary orbit)	Operational (Regionally)
2	GALILEO [28]	European Union	Global	30 (10 satellites will evenly occupy each of the three orbital planes), all in the Medium Earth Orbit at an altitude of 23,222 km	Underway
3	GLONASS [29]	Russian Federation	Global	27 (requires 24 operational satellites) at an altitude of 19,100 km	Operational
4	IRNSS/ NAVIC [30]	India	Regional	7 (3 in Geostationary orbit and 4 in Geo-Synchronous orbit	Operational
5	NAVSTAR GPS [31]	United States	Global	32 (requires at least 24 operational satellites), all in the Medium Earth Orbit at an altitude of approximately 20,200 km	Operational
6	QZSS/ Michibiki [32]	Japan	Regional	4 (3 in QZ orbit and 1 in Geostationary orbit)	Underway

BDS BeiDou Navigation Satellite System, *GLONASS* GLObal NAvigation Satellite System, *GPS* Global Positioning System, *IRNSS/NAVIC* Indian Regional Navigation Satellite System/NAVigation with Indian Constellation, *NAVSTAR GPS* NAVigation Satellite Timing and Ranging Global Positioning System, *QZSS* Quasi-Zenith Satellite System

Despite, the strengths and large application areas, SNS also suffers from many drawbacks. The major drawback is that they cannot provide localization information in an indoor environment. Their accuracy drops considerably in the outdoor environments having obstructions like tall buildings, under bridges or under trees (refer Fig. 2). Researchers have developed several augmentations (space-based and ground based, respectively) to enhance the accuracy, availability, and integrity of stand-alone GPS [33]. Differential GPS (DGPS) and Assisted GPS (AGPS), respectively, are the two developments which can eliminate most of the errors associated with GPS [35]. Even a better precision can be achieved using Wide-area DGPS (WADGPS).

With the current state-of-the-art technology, it has become possible to cheaply embed highly accurate and precise GPS modules into mobile devices, thus, opening new vistas for gaining knowledge about mobility pattern of individuals. Predicting the mobility pattern of individuals or vehicles precisely is extremely valuable mainly in locations-based services (LBSs), in light of the fact that useful information can be made available to the subscribers beforehand. This mitigates the system delay, thereby enlarges the interactivity of services. Several applications, for example, location

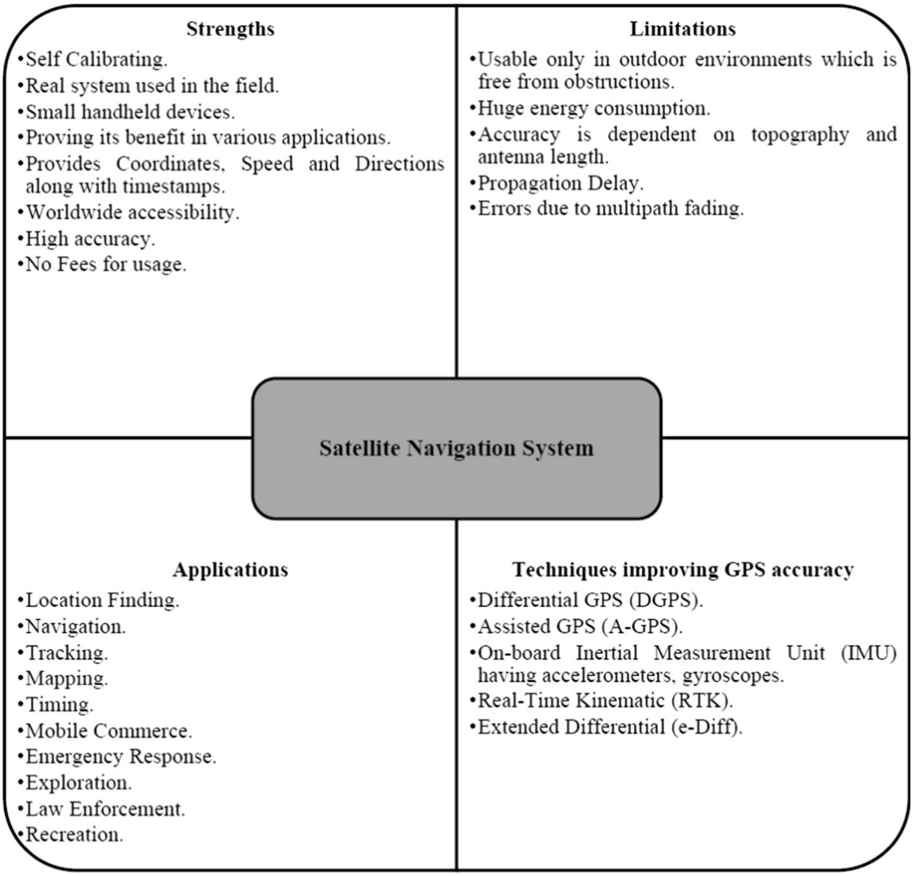

Fig. 2 Strengths, limitations, applications and techniques for improving accuracy, associated with a satellite navigation service

finding, early reminder system, traffic planning, and dead reckoning in GPS, need precise position/co-ordinates. These co-ordinates can satisfactorily help in modeling the mobility of various individuals, groups or vehicles.

2. *Data repositories*
Recently, several attempts have been made to study the human & vehicle movements and collecting positioning data or trace using custom tailored GPS devices or the radio technology (Bluetooth or Wi-Fi). Some trace based, accurate and realistic mobility models can be seen in [34, 36–41]. Two famous and well-used data-sources for armed conflicts are Armed Conflict Location and Event Data Project (ACLED) [42] and Uppsala Conflict Data Program (UCDP) [43]. These are the most comprehensive public collection of political violence and protest data for developing states. However, as stated in [44], there is still a dearth of mobility trace for disaster and battlefield environments, and the existing traces have a limited accuracy. The work in the direction of studying and analyzing traces has already been started in a big way by some researchers, e.g., through the project *Invisible Dynamics*, researchers collected the mobility trace using GPS for locating the movements of Yellow Cab vehicles throughout the greater San Francisco Bay area and named the dataset as *CabSpotting* [45]. Another notable GPS based traces are *CenceMe* and *GeoLife*, respectively [34]. Besides, the datasets mainly used by the researchers from the field of social science, involving diffusion of information among a group of people, contact and friendship network among high school students, and hospital ward dynamic contact network etc., can be accessed from *Sociopatterns* repository [46].
In fact, contributions from the research community, involving painstaking efforts to collect mobility traces has given birth to the repositories like CRAWDAD [47], Sociopatterns [46], UMass Trace [48], Network Repository [49], Foundations of Data and Visual Analytics (FODAVA) [50], Stanford Network Analysis Platform (SNAP) [51], UC Irvine Machine Learning Repository [52] and MobiLib [53]. Here, a user can access archived wireless data traces, contribute his/her own wireless trace data or participate in the development of better tools for collecting, anonymizing, and analyzing data. It is evident that CRAWDAD stands out the most favorite repository among the researchers with a credentials of 120 datasets, 22 tools, 10661 users from 120 countries, and 2453 research papers by the researchers using its datasets or citing CRAWDAD in their research work [47].
Recently, Baudic et al. [54], presented a praiseworthy review on the details of trace collection and processing. Besides, Aschenbruck et al. [44], presented a detailed insight into various trace sources, deploying scenario, device utilized, and various types of dependencies. The authors in [44] also surveyed, comprehensively, the mobility traces collected from the real world projects like: Haggle project, Dartmouth Campus, and ZebraNet etc.
The above datasets are mainly devoted to large, GPS based, collections of traces and related projects. Such datasets fail to provide an appropriate accuracy in indoor environments, which require localization information obtained with the help of sensors or cameras deployed in users' environment. In order to study and characterize the complex indoor propagation environments, several datasets have been collected by the researchers and efficient software tools have also been developed & available in the market. For instance, the dataset for indoor user movement prediction from radio signal strength (RSS) [55] represents a real-life benchmark in the area of ambient assisted living applications as described in [56]. Besides, *CellTrace* [57] and *WinProp* [58], are tools that address Radio Frequency (RF) planning, design, modeling, analysis

and optimization of wireless communication systems within buildings, tunnels, stadiums and in urban environments.

2.2 Connectivity Modeling

2.2.1 Percolation and Diffusion Theory Based Model

The percolation theory and probabilistic epidemic algorithms have been used in the literature [59, 60] to handle the phase transition phenomena in MANETs, which results in an abrupt change in the behavior of the network leading to the appearance of some new property in the system. In fact, by percolation and diffusion theories it is possible to solve two dependent aspects: (1) a good diffusion of information in the network (needed for routing, broadcast and communication) and (2) its connectivity (needed to reach each node) [61]. Recent research from the field of percolation and diffusion theory shows that both may be complementary to each other in the context of MANET [61, 62]. In [63] a percolation theory based framework was proposed to calculate the network reliability.

2.3 Graph Theory Based Modeling

2.3.1 Connected Dominating Sets Based Model

A Dominating Set (DS) of nodes is a subset of network nodes such that a node outside this set is directly connected to at least one member of the DS. A Connected Dominating Sets (CDS) is defined as a set of nodes in a network such that each node is either in the set or adjacent to a node in the set. CDS is another approach of modelling a dynamic network that stems from the field of graph theory and finds its application for routing data among nodes in ad hoc networks [64–67].

2.3.2 Regular Lattice Graph Model

A *d-lattice* is a labeled, unweighted, undirected, and simple graph that is similar to a Euclidean cubic lattice of dimension d, such that any vertex v is joined to its lattice neighbors, u_i and w_i, as specified by:

$$u_i = [(v - i^{d'}) + n](mod\ n) \tag{1}$$

$$w_i = (v + i^{d'})(mod\ n) \tag{2}$$

where n is the number of vertices in the regular lattice, k denotes the number of neighbors to a vertex, $1 \le i \le k/2$, $1 \le d' \le d$, and it is generally assumed that $k \ge 2d$. Hence, 1-lattice with $k = 2$ is a ring, a 2-lattice with $k = 4$ is a two dimensional square grid, and so on [68]. See Fig. 3 for examples of lattice graphs for $k = 2$ and 4.

In wireless ad hoc networks, nodes use radio communications to form links with other nodes. In this model, a probability of connectivity between adjacent nodes is defined as p whereas non-adjacent nodes are indirectly connected via intermediate nodes. As the radio signal power decays with the increasing distance between nodes, the probability of existence of a link varies as a function of the distance between the nodes. So, it is evident that the lattice model can suitably represent an ad hoc network as both networks share the

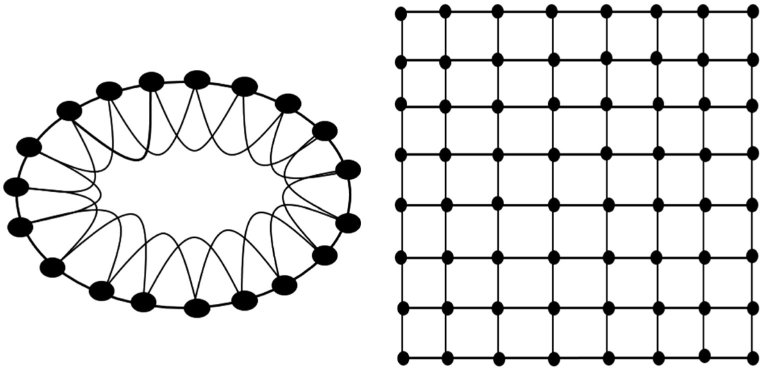

Fig. 3 Examples of lattice graphs: **a** 1-lattice for $k = 2$, **b** 2-lattice for $k = 4$

notion that the distance between nodes influences the probability of existence of a link [69].

2.3.3 Random Geometric Graph Model

A complete graph on n vertices consists of $\frac{n(n-1)}{2}$ edges; however, a random graph involving n vertices constitutes $p\frac{n(n-1)}{2}$ edges, where, p is the probability of a link existence between a specified pair of nodes. The most fundamental assumption in random graph is that the existence or non-existence of an edge between two nodes is entirely independent of the existence or non-existence of any other edge in the network. This may not be true in the case of MANETs, as the active nodes which are within the coverage area of each others are certainly connected. In other words, in MANETs, a node pair having lesser Euclidean distance between them in comparison to their transmission range will have high probability of link availability in comparison to a node pair having a larger distance between them. Therefore, the random graphs of Erdős and Rényi become trivial for studying MANETs [69].

A Random Geometric Graph (RGG) is a graph drawn by placing a set of n vertices independently and uniformly on the unit square $[0, 1]^2$ in a random fashion, and by connecting two vertices if and only if their Euclidean distance is at most the given radius r [70]. The deterministic counterpart of RGG is called Unit Disk Graph (UDG). A graph G is a UDG for a radial distance r, if its vertices can be put in one-to-one correspondence with the centers of circles of radius r in a plane such that two vertices in G are connected by an edge if and only if their corresponding circles intersect. Hence, RGGs which resolve the above stated problem associated with the random graphs have found wide application for modeling link formation/disappearance in MANETs. The application of RGG for MANET modelling can be seen in [8, 71, 72].

2.3.4 Evolving Graph/Time Varying Graph/Temporal Graph Model

The notion of evolving graphs basically consists of formalizing a time domain in graphs. The addition of information about times of interactions in a graph/network, make predictions and mechanistic understanding more accurate. These evolving networks are known with many different names in the literature, i.e., *temporal graphs*, *evolving graphs*, *time-varying graphs* (*TVGs*), *time-aggregated graphs* (*TAGs*), *time-stamped graphs*, *dynamic networks*, *dynamic graphs*, *dynamical graphs*, *spatio-temporal networks* and so on [73].

Formally, a TVG could be seen as a network $G = (V_G, E_G)$, where each node and link has a presence schedule defined for it. Corresponding to each link $e \in E_G$ (node $v \in V_G$) the link existence schedule (node existence schedule) indicates the time instants at which a link (a node) is present, and possibly other parameters they take during each interval [74]. Here, one may assume the presence schedules as a sorted list of intervals. The definition of the TVG model can now be stated as:

Definition Let there be a graph $G(V, E)$ and an ordered sequence of its subgraphs, $S_G = G_1(V_1, E_1), G_2(V_2, E_2), \cdots G_i(V_i, E_i), \cdots G_\tau(V_\tau, E_\tau)$, $\forall\, V_i \in V$ and $E_i \in E$, such that $\cup_{i=1}^{\tau} G_i(V_i, E_i) = G(V, E)$ and each $G_i(V_i, E_i)$ is the subgraph in place during $[t_{i-1}, t_i)$. Let $S_T = t_0,\ t_1,\ t_2,\ \cdots,\ t_\tau$ be an ordered sequence of time instants. Then, the system $G = (G(V, E), S_G, S_T)$ is called an evolving graph.

The graph $G(V, E)$ is called an *underlying graph* of G. This static graph should be seen as a sort of footprint of G, which flattens the time dimension and indicates only the pairs of nodes that have relations at some time in S_T [75]. With the help of the edge and node existence schedules, changes in topology of an evolving graph can be studied [76].

To better understand the concept of TVGs see Figs. 4 and 5; where, Fig. 4a–d, represent the time-evolving topologies of the network during four time slots. Figure 5a represents an underlying graph for an evolving graph of five nodes at $t = 0$. Figure 5b shows TAG at $t = 1, 2, 3$ and 4, with link number 2, 7 and 10 not appearing in any time interval. Figure 6 represents a time line showing contacts between nodes for a TVG at different time intervals. In the following discussion, we present the paradigm shift of network topology modeling towards TVGs.

Paradigm Shift towards TVGs

Earlier, performance analysis of dynamic networks has been carried out by neglecting the time instants of interaction between mobile nodes. This style of analysis produced aggregated graph, which could only depict nodes and links (along with their weights at most), but failed to represent the time at which links were formed or broken. A new combinatorial model for graph modeling and analysis, namely, evolving graph/TVG (discussed above) is becoming popular amongst researchers these days, because of its power to incorporate time domain feature in the form of contact sequences. Although in

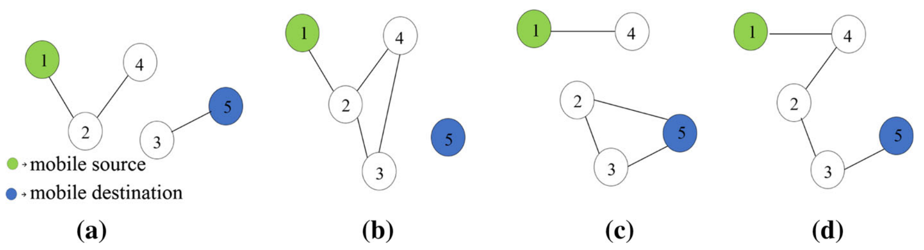

Fig. 4 **a** Snapshot for a TVG of 5 nodes at $t = 1$. Clearly, there is no direct path between (1,5) at this time interval, **b** snapshot for a TVG of 5 nodes at $t = 2$. Clearly, there is no direct path between (1,5) at this time interval, **c** snapshot for a TVG of 5 nodes at $t = 3$. Clearly, there is no direct path between (1,5) at this time interval, **d** snapshot for a TVG of 5 nodes at $t = 4$. There is a direct path between (1,5) at this time interval

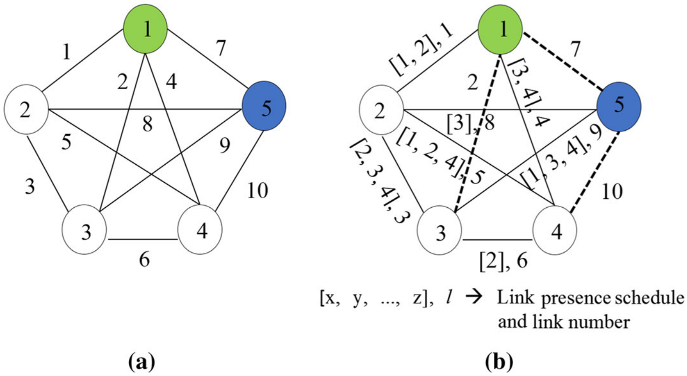

Fig. 5 **a** Complete graph on 5 nodes (K_5) or underlying graph for a TVG of 5 nodes at $t = 0$, **b** time aggregated graph (TAG) of 5 nodes at t = 1, 2, 3 & 4, with link no. 2, 7 & 10 not appearing in any time interval

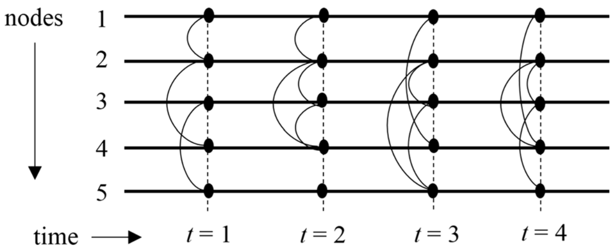

Fig. 6 Time line representing contacts between nodes for a TVG of 5 nodes at different time intervals

TVG the assumption of connectivity does not necessarily hold at a given instant of time, i.e., the network could even be disconnected at every time instant, communication routes generally become available over time and space, enabling broadcasting and routing by means of a store-carry-forward like mechanism [75]. The systems which can be suitably represented as TVG appear to be omnipresent now-a-days. The flow of information via e-mail messages, cellular phone calls, and online networking are few examples that have lately pulled in much consideration. As, TVGs reflect the real environments perfectly in which DTNs operate, therefore, they may be used to model DTNs for evaluating network reliability measures, packet delivery ratio (PDR), average number of link failures during the routing process, routing requests ratio, average end-to-end (E2E) delay and route lifetime. Recently, this model has been utilized in the evaluation of most reliable journey in VANETs [77]. MANETs have also been modelled using this modeling technique [78]. Other dynamic systems that can be modeled as TVGs are human proximity networks, animal proximity networks, human communication, collaboration networks, citation networks, economic networks, brain networks, travel and transportation networks, distributed computing, biological networks, and OMNs [79]. Interested readers are encouraged to explore some of the recent research to get a deeper insight in to the domain of TVGs [73, 75, 79–92].

At this juncture, it is very evident that there is a paradigm shift of research from static graph representation towards the TVGs because of their power to consider the effects of time domain on system topology. However, till date there are not so many methods available to model and analyze the networks varying with time. The primary reasons behind this deficiency are: (a) the field of temporal graphs is relatively young, and (b) it is more difficult to develop methods of performance analysis in dynamic networks, in comparison to the methods available for static networks.

2.4 Radio Propagation Based Modeling

2.4.1 Lognormal Geometric Random Graph Model

The log-normal radio model assumes that the logarithmic value of the received signal power at distance r is normally distributed with standard deviation σ around the logarithm of the area mean power. The magnitude of the standard deviation indicates the severity of signal fluctuations caused by irregularities in the surroundings of the receiving and transmitting antennas. Hekmat and Miegham [93, 94] studied connectivity in MANETs by modeling the network as an undirected RGG. For finding the probability of existence of a link between nodes, they used a radio model based on the log-normal shadowing that takes into account random statistical variations of the radio signal power around its mean power value. These variations are unavoidably caused by the obstructions and irregularities in the surroundings of the transmitting and the receiving antennas, and have two distinct effects on the network. Firstly, they reduce the amount of correlation between links, thereby, causing the RGGs to behave like a random graph with uncorrelated links. Secondly, these variations increase the probability of existence of long links, which in turn, enhances the probability of connectivity for the network.

2.4.2 Propagation-Based Link Reliability Model

As stated earlier, in RGG the mobile nodes in the network can communicate with each other if the Euclidean distance between them is less than or equal to the transmission range of the mobile nodes. Hence, link reliability is theoretically considered as unity under the above criterion. However, even up to the transmission range of the mobile nodes the signal strength deteriorates due to a variety of reasons such as noise, fading effect or interference etc., thereby, decreasing the probability of successful communication. Hence, in propagation-based link reliability model, the link reliability is modelled with a combination of free-space propagation model (FS) and two-ray ground propagation model (TRG) to incorporate the variation in radio signal due to variation in terrain, frequency of operation, speed of mobile nodes, obstacles and other technical factors. Based on this combination, FS-TRG propagation model for modelling link reliability of a MANET as a function of distance has been proposed in [95], and was later utilized in [96] for evaluation of mobile ad hoc network reliability. However, the application of two-ray model in ad hoc networks seems implausible as here both transmitter and receiver are of comparable heights and the inter separation distance between transmitter and receiver is quite less.

2.4.3 Wireless World Initiative New Radio Model

In [97, 98], authors utilized Wireless World Initiative New Radio (WINNER) model for urban scenarios with low antenna heights to study the energy consumption in cellular and device-to-device communication based opportunistic multi-hop networks. They modeled the transmission energy consumption required for a successful communication between two nodes, also included WINNER propagation losses, under assumption that the transmission power, P_T is necessary to guarantee the required signal power level, P_R at the receiver, and estimated the transmission power under LOS conditions as:

$$P_T^{LOS}(d) = \begin{cases} \frac{P_R \times 10^{4.1} \times (f/5)^2}{G_T \times G_R} \times d^{2.7}, \ if\ d < d_{bp} \\ \\ \frac{P_R \times 10^{4.1} \times (f/5)^2}{G_T \times G_R \times d_{bp}^{1.73}} \times d^4, \ if\ d \geq d_{bp} \end{cases} \quad (3)$$

where f represents the carrier frequency (in Gigahertz), d represents the separation distance between the transmitter and receiver, h_T and h_R are the transmitter and receiver antenna heights (in meters), and λ is the carrier wavelength (in meters), G_T and G_R represent the transmitter and receiver antenna gain (here equal to 1), and d_{bp} is calculated as $4 \times (h_T - 1) \times (h_R - 1)/\lambda$.

3 Leap from MANETs to MANET-Born Networks

In the past, it was thought that wireless multi-hop networks would find application mainly in combat fields or during some natural calamity for restoring communications and in providing help in search and rescue operations. However, as the novel technologies (such as Bluetooth and Wi-Fi) have been evolving to their maturity, the scenario of ad hoc networking has also dramatically changed [99]. The ad hoc networks are not just a part of theoretical or simulation studies now, but are expected to play a significant role in various applications in near future in conjunction with already existing infrastructure based communication systems.

Recently, several ad hoc networking paradigms like DTNs, OMNs, FANETs, and VANETs (also known as "MANET-born" networks) have evolved from MANETs. These networks have mainly been developed to resolve the issues *viz*., (a) implementation, integration, and experimentation, (b) simulation credibility, and (c) socio-economic motivation, associated with MANETs via their pragmatic development approach [1]. Although the commonalities do exist in these networks, however, a major difference lies in the deployment environment. For instance, in areas where the user density is high, MANET provides high network reliability; whereas, wherever the user density is low and/or the moving speed of the users is high, DTNs achieve a certain level of network connectivity and the performance of MANET decreases drastically in such a situation [100]. An opportunistic network phenomena is mainly based on *store and carry forward* mechanism wherein a data packet is saved for future time instants when a communication link can be successfully established; thereby, is accompanied by an additional delay in data delivery. In opportunistic networking, no assumption is made with regard to the existence of a complete path between two nodes wishing to communicate. In other words, both DTNs and OMNs are deployed in applications that can tolerate large delays and present intermittent connectivity; also, they utilize some agent usually called as ferry or data mules for propagating messages from source to destination. Frodigh et al. [99] reviewed and elaborated the concept of networking wireless communication devices and underscored the challenges faced by the researchers while network formation and routing in these networks.

As these new (MANET-born) ad hoc networking paradigms use more realistic and utilitarian development foreplan involving *application oriented development*, *complexity* *reduction*, *focussed research*, *realistic simulation models* and *development of real network testbeds*, they have become very successful lately [1]. With the improvement in wireless networking devices and evolution of various techniques to harness the precise localization information from the satellite navigation systems, the real potential of these MANET-born networks has started to become clearly visible now. The present research trends shows jump from MANETs to MANET-born networks. Although these networks have huge potential to be deployed in diversified applications, that is, in military battlefields, rural communication, e-commerce, collision avoidance, environment and wildlife monitoring and many more, yet, their real implementation involves many grave challenges. In this review, we have listed in Table 4 the application areas and challenges of various multi-hop mobile ad hoc communication paradigms, and presented in Table 5 a comparison of main features of these networks.

Further, in the forthcoming section we discuss some simulators, emulators and testbeds developed for studying such dynamic networks.

4 Simulators, Emulators and Testbeds for Dynamic Networks

Increasing research efforts towards time varying networks/dynamic networks requires new strategies to effectively study the various features associated with these networks. A brief review of the representation styles developed to analyze the time varying networks may be seen in [101–105]. Various network simulation/visualization tools & packages, emulators and testbeds have also been developed for studying the dynamics and complex processes occurring in large networks emanated from different fields of study such as social science, biology, citation networks, World Wide Web (WWW), Internet, MANETs, VANETs, OMNs and DTNs etc. The following sub-sections give an extensive taxonomy of these simulation/visualization tools, emulators and testbeds, respectively.

4.1 Simulation Tools

Simulation is widely used in the domain of wireless networks, where one can find a number of free and commercial simulation platforms. To the best of our knowledge, there is a lack of a detailed taxonomy on these simulation and visualization tools in the literature. We have compiled 22 popular simulation and visualization tools in Table 6 with a brief description of each. Out of these 22 simulators, ns-2 and OMNeT++ have widely been used for studying the performance of various routing protocols in MANETs. Besides, the Pajek is extremely popular among researchers working on large graphs and ONE is a well-known DTN simulator.

4.2 Emulation Tools and Testbeds

A rich literature is present on the topic of emulators and testbeds [139–142]. Choosing an appropriate emulation/testbed-platform for validation of research outcomes is an endeavor on its own. There is no panacea for all possible application scenarios, but a compromise between characteristics, such as scalability, realism, performance, and cost has to be reached. Table 7, provides a compilation of 14 emulators and testbeds (along with their features) available for experimenting and modeling wireless ad hoc networks. In Table 8, we have specifically collated 12 real prototypes for target tracking and performance

Table 4 The application areas and challenges of various multi-hop mobile ad hoc communication paradigms

S. no.	Network type	Applications	Challenges
1.	DTNs/ OMNs	Wildlife monitoring, deep space exploration, rural communication, lake quality monitoring, emergency services and smart transportation	1. Routing through space and time demands new efficient routing protocols 2. Need of new mobility models and evaluation of the routing performance 3. Designing new systems for the use of DTNs in disaster scenarios 4. Strict bandwidth, buffer space and energy constraints for applications 5. Evaluation of network reliability in DTNs where no contemporaneous end-to-end path exists is cumbersome 6. Problem of topology control in DTNs arising due to high rate of mobility and topology change
2.	FANETs	Search and destroy operations, law enforcement, remote sensing, border surveillance, forest fire prevention, wind estimation, polar weather monitoring, hurricane observation, pollutant studies, disaster monitoring and traffic monitoring	1. Ground reflection effects 2. Shadowing resulting from the UAV platform and onboard electronic equipment 3. The effect of aircraft attitude (pitch, roll, yaw etc.) on the wireless link quality 4. Interferences and hostile jamming 5. Need of new routing algorithms 6. Development of new physical layer designs for three dimensional environments
3.	MANETs	Military battlefield, emergency services, education, e-commerce, sensor networks, home/office wireless networking and context aware services	1. Need of new mobility models, validated with traces, for different scenarios 2. Need of new efficient routing protocols 3. Improving connectivity among crew members in rescue operations. Minimize packet collisions 4. Address problem of hidden and exposed terminals 5. Address security problems
4.	VANETs	Collision avoidance, road obstacle warning, safety message disseminations, games and multimedia streaming	1. Need of special mobility models on the basis of traffic flow 2. Secure broadcasting schemes for emergency scenarios 3. Study of effects of driver behavior 4. Need of new efficient routing protocols specific to VANETs

Table 5 The comparison of main features of multi-hop mobile ad hoc communication paradigms

S. no.	Network type	Attributes					Remarks
		Topology change	Node density	Mobility	Location prediction	Computational power	
1.	DTNs/ OMNs	Fast	Medium-Low	Medium, Unexpected	GPS, DGPS, AGPS	Limited	1. Instantaneous end-to-end connectivity never exists 2. Long delivery delay 3. Provides new ICT based applications in the remote areas of the world
2.	FANETs	Very Fast	Very low	Very High	GPS, DGPS, AGPS, Inertial Measurement Unit (IMU)	High	1. Frequent link outages due to highly mobile nodes 2. Reliability is a critical issue 3. Distances between FANET nodes are much longer
3.	MANETs	Slow	High	Low-Medium, Unexpected	GPS	Limited	1. End-to-End connectivity is available 2. Short delivery delay 3. High transmission reliability
4.	VANETs	Fast	Medium-High	High, Predictable and Constrained by lanes and traffic.	GPS, DGPS, AGPS	High	1. Connectivity and coverage vary with the traffic condition, which is variable both in time and space 2. Topology of the network could be affected by driver's behavior 3. Small effective network diameter

Table 6 Simulators for modeling and visualizing dynamic networks

S. no.	Name	License type	Brief description
1.	Adyton [106]	Free	A simulation software for opportunistic networks, simulating a plathora of routing protocols and real-world contact traces
2.	DTNTES [107]	Free	A trace analysis tool used to extract various information from real trace like DieselNet
3.	Gephi [108]	Open source and Free	A powerful network/graph analysis software which can generate and analyze time varying graphs, and propose a timeline component where a slice of the network can be retrieved
4.	GlomoSim [109]	Open source	GloMoSim is a library-based sequential and parallel simulator designed as a set of modules in the layered architecture for wireless networks; each module simulates a specific protocol in the protocol stack
5.	ICONE [110, 111]	Free	Modified ONE simulator is a collection of add-ons that transform the original ONE simulator into a simulator having Named Data Networking (NDN) capability
6.	Igraph [112]	Open source and Free	A powerful package/library which can be embedded into a higher level programming language (like Python, Perl or GNU R) and is capable of handling huge graphs with millions of vertices and edges. Various igraph libraries can be accessed from Github repository
7.	JiST/SWANS [113, 114]	Free	JiST is a high performance java based discrete simulator and SWANS is a complete library for simulation of MANETs running on the JiST engine
8.	J-Sim [115, 116]	Open source	An independent, extensible, and reusable modeling and simulation framework/ environment developed in Java for Wireless sensor networks (WSNs)
9.	KUMONOTE [117]	Free for non-commercial use	A powerful network/graph analysis software which can plot degree distribution, generate randomized graph, extract giant connected component, convert the given network in format which can be analyzed with Pajek and visualize the network connectivity
10.	MADHOC [118, 119]	Free	Designed for implementing new environments, new mobility schemes and new applications in Delay Tolerant MANETs

Table 6 continued

S. no.	Name	License type	Brief description
11.	MATLAB [120]	Commercial	A high-performance, multi-paradigm numerical computing environment for computation, visualization, and programming. The Matlab can be used for machine learning, signal processing, image processing, computer vision, communications, computational finance, control design, robotics, and much more
12.	NetMiner [121]	Commercial	A network analysis software package which helps perform data transform, network analysis, statistical analysis, and network visualization
13.	ns-2 [122]	Open source	Event-driven simulator designed specifically for research in computer communication networks. It now contains modules for numerous network components such as routing, transport layer protocol, application, etc
14.	ns-3 [123]	Open source	A discrete-event network simulator designed to cater the needs of modern networking research for Internet systems; ns-3 is intended to eventually replace the popular ns-2 simulator by a modern simulator targeted primarily for research and educational use
15.	OMNeT++ [115, 124]	Free for non-profit use	Discrete event simulation platform, designed to support the simulation of telecommunication networks and other parallel and distributed systems
16.	ONE [125, 126]	Free	A well-known Delay Tolerant Network (DTN) simulator designed for evaluating DTN routing and application protocols. It allows users to create scenarios based upon different synthetic movement models and real-world traces
17.	OPNET/ Riverbed Modeler [127]	Commercial version, or Free to qualifying universities worldwide for academic research and teaching	Discrete-event simulator to design, model, and analyze communication networks. It can model various networks and technologies such as VoIP, TCP, OSPFv3, MPLS and IPv6, etc
18.	Pajek [128–131]	Free for non- commercial use	Extremely popular program package for analysis and visualization of large networks
19.	Ptolemy-II [132–134]	Open source	Can model, simulate and design concurrent, real-time, embedded systems with focus on assembly of concurrent components

Table 6 continued

S. no.	Name	License type	Brief description
20.	Qualnet [135]	Commercial	A simulation platform which assists in simulating the behavior of real communications networks, allows user to design, analyze, and optimize various scenarios
21.	SoNIA [136, 137]	Free	A powerful simulation platform for testing and comparing layouts and techniques and for browsing attribute-rich network data for animating network dynamics over time
22.	SSFNet [138]	Open source, Free or available at nominal cost for research purposes.	Java SSF-based discrete-event simulator for modeling and simulation of Internet protocols and of large and complex systems at and above the IP packet level of detail

DTNTES Delay Tolerant Network Trace Evaluator System, *GlomoSim* Global Mobile System Simulator, *ICONE* Information Centric Opportunistic Network Environment, *JiST/SWANS* Java in Simulation Time/Scalable Wireless Ad-hoc Network Simulator, *MADHOC* Metropolitan Ad hoc Network Simulator, *MATLAB* Matrix Laboratory, *ONE* Opportunistic Network Environment simulator, *SoNIA* Social Network Image Animator

evaluation of VANETs, FANETs and DTN/OMNs along with their brief description. However, it seems impossible from the available literature to identify any single ace emulator/testbed.

5 Real World Project Implementations

Recently, a large number of projects have emerged from various universities and research organizations for developing DTNs, FANETs and VANETs to study the performance of such ad hoc networks and to ensue new applications. American Red Cross Apps [173], and Google Public Alerts [174] are two such applications which use internet for the crisis information dissemination. Even, social media platform like Twitter has also been shown to opportunistically spread the tweets using the *Twimight* [175] client for Android phones and the Bluetooth technology. Furthermore, there is an increase in concerted efforts directed towards the development and evaluation of new, efficient routing protocols and mobility models specifically for search and rescue operations in disaster scenarios.

Here, we have collected some real life projects (completed or ongoing) from the literature, executed with a prime objective to study the wireless multi hop networks (MANETs, DTNs, OMNs and VANETs) and to develop new technologies based on the challenges encountered in their implementation. Another objective achieved with these projects is the enhanced confidence that these networks are no underdogs in comparison to infrastructure based networks, and they will help in bringing out new ICT based applications even for those remote areas where conventional infrastructure based network setup is not present or is almost impossible to install.

These projects have helped to: (a) collect real mobility traces of humans and vehicles, (b) develop new ICT based services and (c) provide the internet connectivity and

Table 7 Testbeds and Emulators for modeling and visualizing dynamic networks

S. no.	Name	Brief description	Reported size	Mobility modeling		Testbed	Emulator
				Real	Logical connectivity		
1	APE [143]	Enables large-scale evaluations of ad hoc routing protocols where experiments are repeatable. It has a non-intrusive measurement system that is fully integrated into the testbed environment.	37 physical nodes	✓		✓	
2.	DAWN [144]	Provides network-layer support for real-time Quality-of-Services (QoS) in large, and dense, mobile ad hoc networks.	10 physical nodes	✓		✓	
3.	EWANT [145]	Allows emulation of: RF propagation effects of a huge network spread over hundreds of meters in a very small area, and mobility via an antenna switching mechanism.	4 physical nodes	✓		✓	
4.	HaggleSim [146, 147]	Can replay the mobility traces collected and emulate different forwarding strategies on every contact event.	–	✓			✓
5.	JEmu [148]	Designed to enable the ad hoc routing protocol designer to create and manipulate wireless scenarios with ease.	12 physical nodes		✓		✓
6.	MANE/eMANE [141]	Suite of tools and applications that can be combined and extended as necessary to provide a high-fidelity, scalable emulation environment for mobile wireless networks.	~ 1000 virtual nodes		✓		✓
7.	ManTS [149]	Can build large-scale MANETs, and enables researchers to estimate their IP and upper layers' protocols and applications intuitively, as well as by collected data.	–		✓	✓	

Table 7 continued

S. no.	Name	Brief description	Reported size	Mobility modeling		Testbed	Emulator
				Real	Logical connectivity		
8.	MASSIVE [150]	An emulator which follows the distributed concept, supports interactive manipulation of the emulation process and allows the coupled evaluation of routing protocols and applications.	13 physical nodes		✓		✓
9.	MiNT [151]	Platform for testing and evaluating wireless applications and protocol implementations.	8 physical nodes	✓			
10.	ORBIT [152]	Aims to provide a flexible, open-access multi-user experimental facility to support research on next-generation wireless networks.	400 physical nodes	✓		✓	
11.	SALT/PC-NETSIM [153]	Allows the actual network protocol and operating system code to be tested quickly.	–		✓	✓	
12.	SALT/PRISM [153]	Permits software control of RF connectivity, supports creation of network topologies such as strings, stars, dense groups, or mobile nodes.	24 physical nodes		✓	✓	
13.	TEALab [154]	Provides an environment for studying network attacks and attack detection in ad hoc networking environments.	10 to 30 physical nodes	✓		✓	
14.	TrueMobile [155]	Remotely accessible mobile wireless and sensor testbed which can provide accurate positioning and monitoring, can enable automated experiments by both on-site and off-site users	16 physical nodes	✓		✓	

APE Ad hoc Protocol Evaluation, *DAWN* Density-and Asymmetry-adaptive Wireless Network, *EWANT* Emulated Wireless Ad Hoc Network Testbed, *MANE/eMANE* Mobile Ad hoc Network Emulator/Extensible Mobile Ad-hoc Network Emulator, *ManTS* Test System for MANET, *MASSIVE* Manet Server Suite Incorporating Virtual Environments, *MiNT* Miniaturized Network Testbed, *ORBIT* Open Access Research Test bed for Next-Generation Wireless Networks, *SURAN* Survivable, Adaptive Networks, *SALT/PC-NETSIM* SURAN Automated Laboratory Testbed/PC-based network simulator, *SALT/PRISM* SURAN Automated Laboratory Testbed/Packet Radio Integrated System Module, *TEALab* Tactical Environment Assurance Laboratory

Table 8 Various testbeds for VANETs, FANETs and DTN/OMNs and their brief description

S. no.	Name	Capabilities	Developed at	Reported Size	Navigation	Developed for paradigm		
						VANETs	*FANETs*	*DTNs/ OMNs*
1.	BEAR [156]	Vehicle guidance and control, computer vision based navigation, aerial communication via, dynamic wireless networking and multi - agent coordination	University of California, Berkeley	6 fully instrumented helicopters and 4 mobile ground- based robots	GPS/ Inertial Navigation System (INS), DGPS		✓	
2.	C-Vet [157, 158]	Provides both vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) connectivity	University of California, Los Angeles	30 Vehicular nodes, installed on facility management vehicles	GPS	✓		
3.	Cabernet [159]	Quick data transfer and high throughput in both fleeting and intermittent end-to-end connectivity environments	MIT Computer Science and Artificial Intelligence Laboratory	25 nodes hosted in taxis, however, only 10 nodes were used in experiments	GPS	✓		✓
4.	Drive-Thru [160, 161]	Internet access for the mobile users in vehicles using hot spots along the roads	Technologiezentrum Informatik (TZI), Universität Bremen	–	WLAN hot spots	✓		✓
5.	GENI [162, 163]	Provides a virtual environment for exploring networking and distributed systems architectures and services	GENI Project Office	Hundreds of resources such as virtual machines, links, switches and Wi-Max base stations	–			✓
6.	HarborNet [164]	Allows cloud based code deployment, remote network control and distributed data collection from moving container trucks, cranes,tow boats, patrol vessels, and roadside units.	DRIVE-IN project (a CMU-Portugal research project)	35 communication devices installed in container trucks, tow boats, patrol vessels, administration vehicles, and roadside infrastructure	GPS integrated with the IEEE 802.11p interface	✓		✓

Table 8 continued

S. no.	Name	Capabilities	Developed at	Reported Size	Navigation	Developed for paradigm		
						VANETs	*FANETs*	*DTNs/ OMNs*
7.	MADNet [165]	Emulation of a wide range of mobile networking scenarios and execution of real-world simplified data collection missions	Columbia University	–	GPS			✓
8.	QOMB [166]	Supports various wireless communication models, versatile scenario definitions and direct execution of applications and protocol implementations for DTN-related experiments	Hokuriku StarBED Technology Center, National Institute of Information and Communications Technology, Japan	25 mobile nodes plus 1 fixed communication gateway	GPS			✓
9.	RAVEN [167]	Designed for long duration missions in a controlled environment to emulate the full functionality of an operational UAV system	Aerospace Controls Laboratory, Massachusetts Institute of Technology	Multiple autonomous aerial and ground vehicles	Vision-based sensing and Vicon motion capture provider		✓	
10.	SUAAVE [168, 169]	Ground sensing of various types; atmospheric sampling; and the ability to bridge communications in ad- hoc situations	SUAAVE consortium (University College London, University of Ulster, and the University of Oxford with Engineering and Physical Sciences Research Council)	–	Wireless radio communication and GPS/ Inertial Navigation system (INS)		✓	
11.	UAVRF [170]	Supports vision aided navigation and control; can conducts flight tests even in GPS-denied environments	Georgia Institute of Technology, Atlanta, Georgia	A wide range of unmanned aerial vehicles (UAV) is available at the facility	Vision aided Inertial Navigation Systems (V-INSs), GPS, and DGPS		✓	

Table 8 continued

S. no.	Name	Capabilities	Developed at	Reported Size	Navigation	Developed for paradigm		
						VANETs	*FANETs*	*DTNs/ OMNs*
12.	VDTN [171, 172]	Allows incoming packets to be assembled into large data packets, called bundles, and also evaluates the network performance with a safety application and a traffic jam system.	Instituto de Telecomunicações, Next Generation Networks and Applications Group (NetGNA), Portugal and by Fiat Automobile, Brazil,	3 vehicles and 1 relay node	GPS	✓		✓

BEAR BErkeley AeRobot, *GENI* Global Environment for Network Innovations, *QOMB* Quality Observation and Mobility Experiment Tools on starBed, *RAVEN* Real-time indoor Autonomous Vehicle test Environment, *SUAAVE* Sensing, Unmanned, Autonomous Aerial Vehicles, *UAVRF* UAV Research Facility, *VDTN* Vehicular Delay-Tolerant Networks communication facility in the remote areas particularly the rural areas and small towns of developing countries like India, Cambodia and Kenya. We have collated the information for 14 such projects along with their important features and funding sources in Table 9. Interested readers can refer the cited papers and references therein for finding more information related with the considered projects.

6 Reliability Evaluation

Often, we need measurable quantities to quantitatively assess the degree to which a system is able to provide the required services. One such performance measuring attribute is reliability. For example, the reliability of a MANET can measure how reliably a packet sent by a source node can be received by a destination node. Though, connectivity, routing protocols, mobility models, energy conservation, security issues and various applications etc., of MANETs have been widely studied in the last decade, yet, the reliability evaluation of these dynamic networks is still in its nascent stage.

The reliability evaluation techniques for static infrastructure based networks are well defined and understood. The literature in this domain contain a plethora of algorithms/techniques. Most of these algorithms originate from graph theory and Boolean algebra, such as enumeration, inclusion-exclusion principle based, sum of disjoint products (SDP) based, decomposition/factoring theorem based, transformation methods, Binary Decision Diagram (BDD), direct methods and approximation method etc., [201–204]. But, this advantage is absent with MANETs and alike because their topology shows dynamicity and environmental conditions show huge variations affecting their transmission range. Hence, for MANET-born networks the existing analytical approaches of reliability analysis are found to be impractical.

The modeling of the erratic topology, node mobility, phase transition, link failure, PDR, routing requests ratio, E2E delay, route lifetime and the reliability analysis are some of the challenges that a MANET and alike networks poses to the reliability research community. Table 10 presents a list of performance measure metrics studied by the researchers for evaluating the performance of wireless ad hoc networks.

Recently, a concerted effort towards evaluating the reliability of MANETs has been undertaken by the researchers. This challenging issue of wireless networks has mainly been addressed using Monte Carlo simulation because it provides a feasible alternative in dynamically changing environment [9] or with the help of ubiquitous analytical approaches of infrastructure based network, like one using SDP [224] to compute the expected hop count and reliability [210]. It is worth mentioning here that, though simulation method is a tool of great significance, especially in the areas where analytical methods are inappropriate and testing over real system is riskier and costly, it has its own limitations. For instance, if the simulation does not reflect an important aspect of reality, it can not give insight into the operating characteristics of the system which the developers are studying. Generalization and lack of rigor can lead to wrong conclusions or inappropriate implementation decisions. Hence, one must be very careful while choosing parameter values that are used as input for simulators [225, 226].

Recently, in [217], authors have utilized logistic regression based modeling followed by simulation in ns-2.35 simulation software to evaluate ad hoc network reliability. Some papers, utilizing the techniques other than simulation for reliability evaluation of MANET are [205, 212, 213, 227], where a new method based on universal generating function for

Table 9 Few real life projects implementing wireless ad hoc networks (MANETs, DTNs and VANETs)

S. no.	Project name	Brief description	Funded by	Device	Scenario/ environment	Start	Duration
1.	Challenged Internet Access Network Technology Infrastructure (CHIANTI) [176, 177]	The main objective of this project was to provide services like internet connectivity in fast moving vehicles such as trains, by integrating and expanding existing core internet architecture and developing solutions for mobility support.	European Union	Existing Internet and CHIANTI software	Nomadic, and vehicular	2008	2 Years
2.	Continuous Displacement Plans Oriented Network (CoDPON) [178–180]	Aims to provide electronic health care for riverine communities of Marajó Archipelago, located in the north of Brazil, through VANETs	FIDESA	Boats, Peers, Base Stations and Hot Spots	Riverine	2010	Ongoing
3.	DakNet [181, 182]	Aims to provide affordable Internet services to citizens in remote areas of developing countries like India and Combodia	NGOs like American Assistance for Cambodia/ Japan Relief Fund (AAfC/ JRF) and governments	Mobile Access Points (MAPs)	Remote regions	2003	Ongoing
4.	Haggle [183]	Designed to enable communication in the presence of intermittent network connectivity, which exploits autonomic and opportunistic communications. Four experimental data sets were gathered by the project, and are referred to as Infocom05, HongKong, Cambridge, and Infocom06	European Commission under the Information Society Technologies Programme	iMotes or Smart phones	Transportation and remote regions	2006	4 years
5.	Invisible Dynamics: Cabspotting [45, 184, 185]	Online system to anonymously track and record the movements of Yellow Cab vehicles throughout the greater San Francisco Bay Area	The Exploratorium of San Francisco	GPS, Taxi cabs	Urban street	2008	30 days
6.	MIT Reality Mining Project [186]	Used mobile phone data to extract patterns that predict future human behavior. It is first mobile dataset with rich personal behavior and interpersonal interactions	–	Bluetooth and Mobile phones	Campus and laboratory	2004	9 months

Table 9 continued

S. no.	Project name	Brief description	Funded by	Device	Scenario/ environment	Start	Duration
7.	Sámi Network Connectivity (SNC) [187, 188]	Aimed to provide internet connectivity to reindeer herders in the remote areas of Laponia region in northern Sweden	Interreg programme	Tablet PCs, laptops, radio, and data relays.	Mountains	2002	5 years
8.	SARAH [189]	Started with an objective of supporting communication in Delay-Tolerant Mobile Ad Hoc Networks (DT-MANETs). The project also focused on the security issues cropping up in the delay tolerant environment due to the lack of end-to-end connectivity	French National Research Agency (ANR)	Laptops, smartphones, vehicles or robots	Rural, urban or wildlife habitat	2005	3.5 years
9.	Sensor Networking with Delay Tolerance (SeNDT) [190, 191]	A project using sensor nodes for environmental monitoring *viz*., lake water quality monitoring and roadside noise monitoring; designed for public authorities, NGOs and/or corporates	Enterprise Ireland	SeNDT nodes	Rural and urban areas and motorways	2002	2 Years
10.	Terminodes [192, 193]	The project identified technical challenges in design of large-scale, self-organized MANETs and primarily focused upon studying, prototyping and finding feasible solutions for them	Swiss	Terminodes	Wide area (city, region or country)	2000	10 years
11.	Technology and Infrastructure for emerging Regions (TIER) [194]	Aims to address the challenges in bringing the Information Technology revolution to the masses of the developing regions of the world. The project utilizes custom-tailored hardware/software, specific for a region, for providing internet and communication facility.	USAID, Blum Center for Developing Economies and Philippine-California Advanced Research Institutes Project	Custom tailored hardware/ software	Rural and small town	2004	Ongoing

Table 9 continued

S. no.	Project name	Brief description	Funded by	Device	Scenario/ environment	Start	Duration
12.	UMass DieselNet [195–197]	A vehicle based delay tolerant communication network operating in a micro-urban area around Amherst, MA, by the Amherst branch of the Pioneer Valley Transport Authority (PVTA)	DARPA and National Science Foundation (NSF)	GPS, HaCom Open Brick compute, and Buses	Campus	2004	3 years
13.	Underwater Acoustic networks (UAN) [198]	Aimed to develop and test underwater wireless network for monitoring and protection of critical infrastructures located by the sea	European Union	Autonomous Underwater Vehicles (UAVs)	Underwater	2008	3 years
14.	ZebraNet [199, 200]	Focused upon wildlife tracking across large regions of Mpala Research Centre in central Kenya. The project integrated computing, wireless communication, and non-volatile storage along with GPS and other sensors	National Science Foundation (NSF) Information Technology Research (ITR) grant	GPS, Flash memory, wireless transceivers and a small CPU	Wildlife habitat	2004	~ 1.5 years [Actual deployment for approximately 17 days]

Table 10 Metrics/performance parameters for analyzing performance of ad hoc networks

S. no.	Performance measure metrics	References	Remarks
1.	Bandwidth consumption ratio	[205]	Calculated by comparing the amount of energy expended by different protocols, by plotting a graph between energy ratio and node velocity.
2.	Capacity	[206–208]	Evaluated the capacity related reliability as the probability of successfully transmitting the required flow from source to destination node.
3.	Control overhead	[205]	Calculated based on the ratio of node velocity to the overhead ratio
4.	Coverage area	[9, 71, 96, 206, 208, 209]	Size of simulation region is varied thus changing the network range
5.	CPU time	[210, 211]	Used for estimating the execution time of an algorithm and/or complete simulation
6.	Delivery ratio	[205]	Calculated by plotting the node velocity vs. the packet delivery, while transferring packets to the destination with high velocity
7.	Delivery time	[212, 213]	Represents the time to deliver the information from source to destination node
8.	E2E delay	[77, 205]	Represents the average time between the sending and receiving times for packets received. This can also be used to find delay ratio.
9.	Hop count	[210]	This metric is helpful in designing an optimal topology with hop count constraints for provisioning QoS in delay sensitive applications
10.	Iterations	[209, 211]	This metric is used to find the effect of change in the number of iterations on the network performance
11.	Link failure	[77]	This metric is used to evaluate the average number of link failures during the routing process
12.	Mean Time to Failure (MTTF)	[214, 215]	MTTF is used as a metric to represent link expiration time and also to observe the effect of its variation on throughput
13.	Network size	[9, 71, 96, 205–209, 211, 215–220]	Number of nodes in a given geographical area is varied
14.	Node energy	[214]	This metric explored the effect of variation in node energy on the reliability
15.	Node speed	[209, 215, 217–219]	This metric is used to find the effect of change in the node speed on the network performance
16.	Packet drop ratio	[205]	Calculated as the node velocity to the number of the packets dropped

Table 10 continued

S. no.	Performance measure metrics	References	Remarks
17.	PDR	[77]	Represents the average ratio of all successfully received data packets at the destination node over all data packets generated at the source node
18.	Probability of link existence	[211]	This metric explored the effect of variation in the probability of link existence on reliability. The results suggest that there is a directly proportional relation among them
19.	Routes	[77, 221]	This metric is used in the literature to find average lifetime of the discovered route. A longer lifetime means a more stable and more reliable route
20.	Routing request ratio	[77]	Evaluated as a ratio of the total transmitted routing requests to the total successfully received routing packets at the destination
21.	Throughput	[205, 214]	This metric is used in the literature to find the rate of successful message delivery over a communication channel
22.	Time Between Failures (TBF)	[222]	The metric denotes period between successive path set failures
23.	Transmission cost	[212, 213, 223]	Represents the cost to transmit the information from source to destination node
24.	Transmission range	[9, 71, 96, 206, 208, 209, 221]	This metric is used in literature to study the effect of variation in the maximum distance within which the data transmitted by a node can be correctly received by its adjacent nodes
25.	Volatility	[207, 209]	This metric describes the frequency and scope of changes to the connectivity configuration of the network

evaluating reliability of MANET is proposed. In [223], authors have utilized factoring method to evaluate reliability of MANET. Rebaiaia and Ait-Kadi [228] have proposed polygon-to-Chain and series-parallel reduction for evaluating reliability of MANETs. In [218], authors modified the reliability evaluation algorithm for computer networks proposed in [229] to evaluate the reliability of MANETs with imperfect nodes. Ahmad and Mishra [230] have used critical node detection based approach for reliability evaluation of large scale MANETs. A stochastic link failure model was used in [231] for reliability evaluation of wireless multi-hop networks. A list of research papers published for the reliability evaluation of MANETs is provided in Table 11, which is by no means exhaustive. More solutions and understanding is expected to arise in the future. It is clearly evident from Table 11 that simulation has mostly been used for reliability evaluation in MANETs.

Table 11 Reliability evaluation of MANETs

S. no.	Technique	Key references
1.	Critical node detection	[230]
2.	Factoring method	[223]
3.	Logistic regression	[217]
4.	Modifying algorithm in [229]	[218]
5.	Polygon-to-chain and series-parallel reduction	[228]
6.	Simulation	[9, 71, 96, 206–209, 211, 214–217, 219–222, 232, 233]
7.	Stochastic link failure model	[231]
8.	SDP	[210, 234]
9.	Universal Generating Function Technique (UGFT)	[205, 212, 213, 227]

Apart from the research efforts dedicated towards the issues related with the reliability evaluation of MANETs and alike, several papers concerned with the connectivity issue of these networks have also been published. The famous model *viz*., TVG, has been utilized to address the issues like mobility pattern, changing topology and connectivity of such networks [74, 235]. In [236], authors have proposed a method to evaluate the MANET connectivity by taking inter-node communication probability and physical connectivity status into consideration. In [237], authors have proposed a probabilistic connectivity matrix to assess the quality of network connectivity for wireless networks, which are inherently unreliable. It was demonstrated that the largest magnitude of eigenvalue of probabilistic connectivity matrix (which is positive) quantifies the quality of network. This work resembles with the recent work of Brooks et al. [238], in which a slightly different probabilistic version of the adjacency matrix is considered, wherein, (i, j)-th entry of the matrix represents the probability of having a direct connection between distinct nodes i and j and entries $\forall i = j$ are set to zero. Moreover, in [238] authors also presented a range-limited graph model for the ad hoc networks.

7 Future Prospects

In order to facilitate a hassle-free communication within ad hoc networks, a variety of routing protocols have been proposed in the recent past. Almost all MANET routing protocols mainly aim to provide a communication platform that is fault tolerant to frequent path breaks, expends minimum processing power and bandwidth to provide high reliability. Some praiseworthy review papers on routing protocols for MANETs can be seen in [239–241]. Although many routing protocols have already been devised and presented in the literature, many new protocols are being proposed almost every day. Hopefully, this field will continue to be favorite and will garner more attention from researchers.

Ad hoc networks are generally energy starved and their network topology and energy consumption are considerably affected by the transmission range of nodes. Hence, in order to reduce energy expenses in data transmission, there must be a trade-off between energy consumption and transmission range to find an optimum balance between them. There are some studies [242, 243], which analyzed the critical transmitting range for connectivity in wireless ad hoc networks. This is another field, which has huge potential of furthering the research.

An experiment conducted by Milgram [244] verified the *small world phenomena* on social networks. In [245], the phenomena of *small world* was proven to be applicable in mobile opportunistic networks as well. Also, it was shown that a destination node could be reached by a small number of relays; hence, opportunistic mobile networks have small diameter. Tang et al. [246] investigated and confirmed the *temporal small world* behavior in social and biological networks. They inferred that these networks have highly clustered links in time, and nodes with small average temporal distances. A visible impact of this phenomena in dynamic networks can be seen in information diffusion throughout the network or in studying clustering coefficient and calculating other parameters like betweenness centrality and closeness centrality.

Another prospective field is mobility trace collection. Although synthetic mobility models along with Monte Carlo simulation method have been utilized in performance analysis, yet, these models fail to mimic reality. A thorough study of the individual movements can be successfully done with GPS data mining. Many studies are going on in this direction and many more will certainly evolve with time.

The domain of reliability evaluation of dynamic networks is also in its nascent stage as the algorithms and techniques available for static networks cannot be directly applied on these networks.

Although a lot of research work has been undertaken for the performance evaluation of ad hoc networks, but, as the number of users with smart phones are increasing tremendously, new robust applications needs to be designed addressing the various challenges. This demands testing of the applications in reality. Though, many testbeds, simulators and emulators have been built, yet, there is no panacea. Hence, new generic testbeds need to be built which can test different paradigms with great efficiency into the real application environments.

Some other worth mentioning challenges for future research are:

1. Usually researchers have considered that all the devices in the system are homogeneous, that is, manufactured by the same company and have similar bandwidth, energy, processing power, and storage capacity. This assumption reduces the complexity of the simulation. However, in reality heterogeneous devices must be considered for simulation. Hence, the research in this area needs more attention.
2. Secure and robust techniques for transmitting the information over wireless media must be comprehensively taken into account.
3. Various new models, exhibiting different aspects of diverse real scenarios need to be developed.
4. Traces collected using GPS may have missing values or can give biased results; hence, more studies based on traces are necessary to validate any proposed mobility model. In addition, the performance of routing protocols should also be evaluated using real traces for more credible performance evaluation.
5. Flow, capacity and other constraint based performance analysis of the multi-hop ad hoc networking paradigms needs to be explored in disruptive environmental conditions because of the frequently changing end-to-end connectivity and highly fluctuating link capacity.
6. The fusion of routing technologies between MANETs and DTNs has already been demonstrated successfully in [100, 247]. However, the interoperability between other paradigms like FANETs, VANETs, MANETs and DTNs needs attention.

The characteristics of ad hoc networks (or the complete domain of wireless networks) is quite dynamic. The research in this domain has been undertaken from several perspectives in the past, still active at present and shall be continued in near future to devise new performance metrics and evaluation techniques for such dynamic systems. We are hopeful that in the near future many new developments will take place in the above directions.

8 Conclusion

In this paper, we have made an attempt to comprehensively summarize the current state-of-the-art research in the area of wireless ad hoc networks varying from MANETs, DTNs, FANETs, OMNs to VANETs from multiple dimensions. We have provided a comprehensive account of the major advancements in the domain of wireless multi-hop networks by highlighting the main results along with the key research and review papers published recently. For this reason, we have avoided description of the mathematical models, their derivations and formulas involved. We have compiled various discussions with figures and tables.

We are hopeful that this survey will support the novice readers to have a better overall understanding of the domain and assist them to start conducting research quickly. The foremost contributions of this survey are:

First, we reviewed various models available in the literature for studying different aspects of wireless ad hoc networks, accompanied with various tools for studying mobility of human beings and vehicular traffic (see Table 1). We found that, during the last decade plenty of research efforts to mitigate the challenges associated with the modeling have been made; at present, the pool of research in this direction is quite rich and an ample number of research papers have already been published.

Second, we highlighted various data repositories, which may be accessed for downloading and validating various *traces*. We discussed in detail about the SNS along with their strengths, limitations, and applications. We also tabulated different SNS variants (see Table 3), operating or in progress, across the globe and surveyed their increasing usage in location prediction, trace collection and mobility modeling along with inherent challenges.

Third, we found from the literature that currently the research momentum is shifting from MANETs to MANET-born networks. Besides, we also compared different multi-hop ad hoc network paradigms and listed their challenges in Tables 4 and 5.

Fourth, we discussed various simulators, emulators and testbeds (Tables 6, 7, 8) along with their specific features and identified some extremely popular simulation and visualization tools amongst the researchers. In Table 9, we covered several worth mentioning real world projects ongoing/carried out throughout the world to address various challenges in implementation and networking in disruptive environments.

Fifth, we dealt with an important aspect of every network i.e., reliability and identified various performance measure metrics and tabulated them in Table 10. Further, we collated in Table 11 various research papers published in the literature for the reliability evaluation of MANETs. We also established from Table 11, that the maximum number of publications utilize simulation for the reliability evaluation of MANETs.

At last, we outlined various challenges for future research.

Although we have discussed the various developments in the field of wireless ad hoc networks in terms of: (1) the available techniques for modeling MANETs, (2) trace collected and data repositories and (3) their reliability evaluation, yet the present state-of-the-art with respect to the models, traces and reliability evaluation seem to be at nascent stage and still unable to resolve the various associated issues in their entirety. We are very optimistic that in the forthcoming days/years the multi-hop network paradigms will flourish more and will help in bringing out newer and better ICT based applications. We feel that there will be intermixing of different paradigms. Moreover, the performance evaluation of these networks (including times of contacts) in terms of reliability and Quality-of-Services (QoS) will garner more attention and will be assessed more rigorously.

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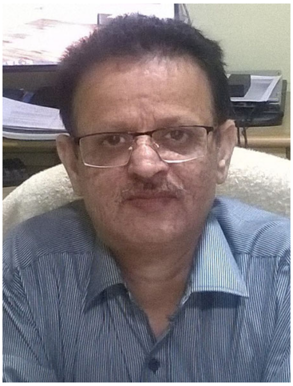
Gaurav Khanna received his B.Tech. Degree in Electronics and Communication Engineering from GBTU, Lucknow, India, in 2011 and M. Tech from School of Information and Communication Technology, Gautam Buddha University, Greater Noida, India, in 2015. He is currently pursuing the Ph.D. degree from Subir Chowdhury School of Quality and Reliability, Indian Institute of Technology Kharagpur, India. His current research interests include wireless ad hoc networks, delay tolerant networks, multistage interconnection networks, performance evaluation, and reliability engineering.



Dr. S. K. Chaturvedi is currently working as a Professor at Subir Chowdhury School of Quality & Reliability, Indian Institute of Technology, Kharagpur (WB) India. He received his Ph. D. degree from Reliability Engineering Centre, IIT, Kharagpur (India) in year 2003. He did his Bachelor's degree in electrical engineering and Master's degree in system engineering and operations research, both from Indian Institute of Technology, Roorkee (erstwhile University of Roorkee), U. P., India in 1988 and 1990, respectively. He has research interests in the area of reliability modeling and analysis, network reliability, life-data analysis, maintenance and optimization. He has published papers in several international journals such as IEEE Transactions on Reliability, Performability Engineering (IJPE), Quality and Reliability Management, Quality, Reliability and Safety Engineering, Uncertain Systems, Risk and Reliability Part 'O', Quality Technology and Quantitative Management, Quality and Reliability International etc. He's two books to his credits. He is also on the review panel of several prominent journals of international repute in his area of research such as IEEE transactions on Reliability, IJPE, IJQRM, IJ System Science, IJ Failure Analysis. He's also a senior member to IEEE and has been Co-Editor-in-Chief to IJPE. He's on the editorial board of International Journal of Mathematical, Engineering and Management Sciences (IJMEMS) and Editorial/advisory board member of Journal of Graphic Era University (JGEU).