[KKHMSt06] *Matthias Kropff, Tronje Krop, Matthias Hollick, Parag S. Mogre, Ralf Steinmetz;* **A Survey on RealWorld and Emulation Testbeds for Mobile Ad hoc Networks;** 2nd IEEE International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities (TRIDENTCOM 2006), Orlando, März 2006, elektronische Veröffentlichung bei der IEEE.

A Survey on Real World and Emulation Testbeds for Mobile Ad hoc Networks

Matthias Kropff, Tronje Krop, Matthias Hollick, Parag S. Mogre, and Ralf Steinmetz
Multimedia Communications Lab (KOM), Technische Universität Darmstadt
{firstname.lastname}*@kom.tu-darmstadt.de*

Abstract

Mobile ad hoc networks allow for the spontaneous formation of communication networks without dedicated infrastructure. Ad hoc networks are not yet ready for large-scale deployment, because several unsolved research challenges persist. Evaluation methods such as analytical modeling, simulation, emulation, and real world experiments aid in addressing these challenges. There is a strong need for tools to support the task of modeling and evaluation to allow for protocol validation, performance analysis, or proof-of-concept implementations. The choosing of appropriate tools is a time-consuming process, which is often unnecessarily repeated, due to limited knowledge-transfer. We contribute an extensive survey covering real world and emulation testbeds to simplify the choice of appropriate research tools and methodologies in the domain of mobile ad hoc networks. In particular, we identify the key attributes of the aforementioned classes of testbeds and thoroughly discuss the state-of-the-art in literature to form a comprehensive classification of available testbeds.

1 Introduction

Today, mobile and wireless communication mainly relies on infrastructure-based cellular networks. In contrast, mobile ad hoc networks (MANETs) are a promising approach for next generation wireless networks to enable communication, even in the absence of infrastructure. However, MANETs have not been widely deployed, yet. The complexity arising from mobile devices, which communicate in an ad hoc fashion via a shared, unmanaged wireless medium, poses various research challenges, many of which are as yet unsolved.

A variety of methods exist to support MANET research. For evaluation and analysis of protocols and algorithms four techniques are well-known: (1) *analytical modeling*, (2) *network simulation*, (3) *network emulation*, and (4) *real world experiments*. The potentials and limitations for methods (1), (2), and (4) have been widely discussed in literature (see, e.g., [11]): Simulation models are often criticized for inaccuracies in capturing realistic node mobility behavior and wireless medium characteristics. Moreover, the available degrees of freedom in instantiating the simulation often leads to biased simulation setups. In contrast, real world testbeds can establish genuine environmental conditions. However, they are typically very much limited in scope and induce high management overhead.

In MANETs, method (4) has recently gained attraction to validate analytical models or verify simulation results. The emulation approach provides a striking compromise between simulation and real world experiments, thus, delivering significant impact to the community. As in real deployments, testing of novel applications can be performed in real-time under realistic conditions, i.e., adhering to device specific limitations, using real protocol implementations, etc. Similar to simulation, the wireless medium effects can be precisely controlled to re-enact network constellations; only the fidelity of the emulation layer controls the precision of the model. Moreover, the switch from emulation to a real world deployments is accelerated, because software code can be reused.

We contribute a comprehensive survey of emulation and real world testbeds for MANETs. In Section 2 we identify the three key characteristics of MANET testbeds, namely *testbed architecture*, *mobility modeling*, and *wireless medium modeling*, and further detail the category of testbed architectures with focus on control paradigms and node abstraction models. In Section 3 we analyze different approaches to model mobility in emulation and real world testbeds. The basic principles of modeling the wireless medium are discussed in Section 4. We include the state-of-the-art in literature to form a comprehensive classification and provide references to related work, i.e., currently existing testbeds for MANETs. In doing so, we aid researchers in identifying the appropriate candidate tools to fit their intended usage profile, thus, presenting a shortcut to a possibly tedious tool selection-process. Section 5 concludes our work.

2 Testbed Categorization and Architectures

Our categorization of MANET testbeds includes three key aspects influencing the functional properties of testbed platforms, i.e., *mobility modeling*, *wireless medium modeling*, and *testbed architecture*. These categories have been derived from the designs of the surveyed testbeds. The chosen implementation of the respective categories determines the possibilities and limitations of the testbed platform such as fidelity, scalability, and performance.

We categorize testbed architecture based on their control mechanisms into *centralized* and *distributed* approaches. Additionally, the degree of *node virtuality* can be differentiated. A summary of the characteristics of the surveyed testbeds is listed in Table 1.

2.1 Centralized control

In the *centralized control* approach a central server emulates the node movement, the virtual scenario environment, and/or the actual state of the wireless medium. The network nodes send their outgoing traffic to a core server, which forwards, drops, or alters the frames/packets according to the actual network topology and wireless medium conditions. E.g., the central server of **JEmu** [4] determines connectivity and collision detection on frame level within a wired network. Similar, **Lin et al.** [17] propose a switch that is based on a standard PC and offers one network interface per connected node. **MobiNet** [20] introduces multiple core control nodes to balance the processing load and mitigate the bottleneck of a single central control entity. Other testbeds following the centralized control paradigm are **NEMAN** [25] and **Judd et al.** [13].

2.2 Distributed control

Distributed control approaches build on nodes that are mutually connected via a wired or wireless shared media. All nodes receive the entire communication and autonomously determine whether incoming packets are accepted or rejected. This decision is typically based on *logical connectivity* (see Section 3), which can be computed from actual topology and medium information in distributed fashion using, e.g., scenario scripts or a central repository.

Nodes of the emulation platforms **MobiEmu** [31] and **NE** [18] control their packet filtering tools according to topology instructions provided by a central server. In contrast, the nodes of **MNE** [19] determine their virtual position from a local random movement function, simulator mobility file, or prerecorded GPS trace. Hereby, synchronization among nodes is achieved by periodically broadcasting the actual coordinates using a distinct control network. The testbed **APE** [24] and the emulation framework **EMWIN** [32]/**EMPOWER** [33] do not use a dedicated control channel, but determine basic on/off connectivity from a predefined event list. In contrast to the aforementioned static approaches the emulation environment **MASSIVE** [23] allows for dynamic mobility scenarios, thus, enabling interactive control of the topology during emulation runtime.

2.3 Virtual Nodes - Node Virtuality

When nodes are further abstracted to software modules, multiple *virtual node* instances can run in parallel on a single physical machine. According to [5] pure node virtuality on a single machine can be regarded as *monolithic emulation*. Monolithic emulation is realized by either setting up parallel network stacks on a single Operating System (OS), e.g., employed in **NEMAN** [25], or by abstracting the node communication to pointer passing between different kernel instances of guest OSs in the user space of the main OS [7]. In contrast, real world testbeds are forced to apply a *one-to-one* node mapping, where each node is hosted by a dedicated emulation machine; the emulation testbeds **JEmu** [4], **Lin et al.** [17], **NE** [18], **MNE** [19], and **APE** [24] apply this *one-to-one* node mapping. While this approach has limited scalability, it enables real world test runs with different types of nodes in a controllable environment. *Hybrid emulation* combines both approaches and consists of physical machines, each one hosting several virtual nodes, and is implemented in **MobiNet** [20], **MobiEmu** [31], **NET** [10] [21], **EMWIN** [32]/**EMPOWER** [33], **ManTS** [8], and **Engel et al.** [3].

3 Mobility Modeling

We abstract the mobility-induced topology dynamics using three different degrees of abstraction: *real mobility*, *channel emulation*, and *logical connectivity*.

3.1 Real Mobility

Testbeds based on *real mobility* change the physical position of nodes either by manually carrying the mobile devices, by using robots, or by antenna switching between fixed propagation locations. In real world testbeds such as **APE** [24], **Gray et al.** [6], **Ritter et al.** [28], **Maltz et al.** [22], and **DAWN** [26] movement patterns are generally very terrain and user specific. Movements can be predefined or carried out individually in a random fashion. Precise scenario replay of real device mobility is limited and requires additional tracking mechanism. E.g., in **Gray et al.** [6] each node is equipped with a GPS receiver while **TrueMobile** [12] applies a camera-based system to determine node position. Additionally changing weather conditions or the presence of irregular obstacles in public areas, i.e., pedestrians or cars, also influence the underlying radio communication (see Section 4). Possible problems during the replay of mobility traces include varying antenna inclination patterns, asynchronous clocks, or imprecise position information.

To overcome the problem of insufficient repeatability, the testbeds **TrueMobile** [12] and **MiNT** [2] are based on radio nodes mounted on robots and operated under laboratory conditions. The radio environment is miniaturized either using adjustable transmit power or, in the case of **MiNT** [2], applying additional radio signal attenuators to confine the transmission range.

3.2 Modeling Mobility by Channel Emulation

As a higher degree of abstraction the approach of *channel emulation* is based on stationary nodes, whose radio signals are altered to emulate the properties of an equivalent time varying radio channel. In **EWANT** [29] each node is stationary and discrete virtual mobility is realized by multiplexing each node's radio signal between four differently located antennas. **ORBIT** [27] also applies this *antenna switching* approach, but is based on a sophisticated 400 node radio grid. The emulated nodes are mapped in real-time to the grid nodes by forwarding egress traffic to the desired physical node instance. Other approaches to realize virtual mobility by means of channel emulation are **Kaba et al.** [14], who propose to guide the radio signals using coaxial cables, **Judd et al.** [13], who base on a DSP-based digital baseband emulation, and **RAMON** [9]. These approaches have in common that the alternation of the radio signals is performed according to the desired mobility scenario and then fed back to the wireless interfaces.

3.3 Modeling Mobility by Logical Connectivity

The mobility modeling approaches stated so far deal with physical radio signals. However, solving problems in the radio-frequency domain can be very costly due to components such as antennas, multiplexers, attenuators, etc. To overcome these limitations, the effects of mobility can be reduced to a *logical node connectivity*, which is applied on packet or frame level. While the physical nodes are stationary, a logical connectivity matrix is calculated from the scenario description. Virtual distances between nodes form the basis of this connectivity matrix and are derived from radio propagation models operating with virtual obstacles and transmit powers. Logical connectivity is closely coupled to the testbed architecture discussed in Section 2. The respective testbeds include **JEmu** [4], **Lin et al.** [17], **MobiNet** [20], **MASSIVE** [23], **EMWIN** [32]/**EMPOWER** [33], **NEMAN** [25], **MobiEmu** [31], **NET** [10] [21], **NE** [18], **ManTS** [8], and **Engel et al.** [3]. **APE** [24], **MNE** [19], and **Gray et al.** [6] support logical connectivity as well as real mobility.

4 Wireless Medium Modeling

Emulation deals with the physical interaction between nodes by modeling the characteristics of the wireless shared medium. The three basic characteristics of the wireless medium are the *radio channel*, the *co-channel interference*, and the influence of *medium access* mechanisms.

4.1 Modeling the Radio Channel

The *radio channel* or *radio link* emulation models the time varying properties of the physical channel between pairs of nodes and depends on the node location/mobility and the surrounding environment. Radio channel effects (e.g., shadowing, free space attenuation, slow and fast fading, scattering, etc.) and hardware specific properties (sensitivity, antenna patterns) are typically emulated using a set of bi-directional links between all nodes.

To avoid unintentional interference, the propagation environment can be reduced to laboratory conditions as in **MiNT** [2],**TrueMobile** [12], and **EWANT** [29]. However, the resulting changes of the signal power delay spread and the decreased signal to noise ratio (SNR) value have to be considered. In **Kaba et al.** [14] the addition of noise generators and phase shifters is proposed to artificially emulate interference and multipath fading. To achieve precise repeatability of radio link conditions, **Lei et al.** [16] add radio interferers to their testbed. The digital baseband emulation used in **Judd et al.** [13] is remarkably flexible; a centralized DSP facilitates the addition of large- and small-scale fading on every signal path between nodes, thus, enabling fine-grained modeling of, e.g., smart antenna technology. **Guffens et al.** [7] determine the SNR at receiver side by applying a modulation scheme, pathloss model, etc. to calculate the resulting bit error rate (BER) and to derive the frame error rate (FER). Similarly, **MobiNet** [20] applies a combination of free space attenuation and two-ray ground reflection model.

MNE [19], **MobiEmu** [31], and **APE** [24] build on a real IEEE 802.11 network. Here, the *distributed control* approach results in capacity limitations if multiple nodes are in close proximity. The approach of *logical connectivity* can neutralize the capacity bottleneck in combination with a wired network technology, however, at the expense of a more complex wireless link emulation. E.g., **EMWIN** [32]/**EMPOWER** [33] allow to set link properties, e.g., packet latency, packet drop, or bit error rate. In **NET** [10] [21] a traffic shaper reduces the transfer rate of the Gigabit Ethernet interface to the desired value of a wireless interface, **Lin et al.** [17] and **NE** [18] shape the egress traffic of the Ethernet interfaces by an additional token bucket mechanism. However, differences of payload size still exist and can result in unrealistic dynamic saturation effects.

4.2 Modeling Co-Channel Interference

Co-channel interference, i.e., radio signals below the receiver's sensing threshold but inducing interference to the receiving system, is a result of spatial frequency reuse and is measured in the signal to noise and interference ratio (SINR). Real world and miniaturization testbeds, e.g., **MiNT** [2] and **TrueMobile** [12], incorporate SINR value naturally. Again, channel emulators, e.g., **Judd et al.** [13], allow to incorporate dynamic interference with a high modeling fidelity, thus, outperforming software models, which are often restricted to a single signal detection threshold. **MobiNet** [20] emulated co-channel interference using the *logical connectivity* approach. The centralized emulation controller drops a frame if the receiver-side difference of the virtual signal strength of two colliding frames is below a certain threshold.

4.3 Modeling Medium Access

Today, most emulation testbeds are mimic IEEE 802.11 based MANETs. If the wireless medium is replaced by a wired one, the medium access procedures, e.g., CSMA/CA or RTS/CTS, need to be carefully transferred into the wired domain. In addition to access delays and dynamic bandwidth limitations, link layer functionalities, such as backoff-timers or frame collisions detection have to be considered.

In *centrally controlled* emulation testbeds based on *logical connectivity*, e.g., **JEmu** [4], the collision detection and bandwidth adjustment can be easily implemented at the core unit. For emulations using *distributed control* two methods, the use of a central medium server and the distributed emulation of the shared media, are applied. Examples for the server based approach are **ManTS** [8] and **EMWIN** [32]/**EMPOWER** [33], where each communication attempt is initiated with a medium state request, possibly triggering the backoff mechanism. Distributed emulation of the shared medium is performed in **NET** [10] [21], where nodes sharing the same virtual wireless medium are connected by a VLAN. Outgoing frames are send as broadcast and the medium state is determined by means of a virtual network allocation vector for each frame.

5 Conclusion

Choosing the appropriate testbed-platform for validation of research results is an endeavor on its own. In our work, we contributed a comprehensive survey of emulation and real world testbeds for MANETs. Our categorization in *testbed architecture, mobility modeling*, and *wireless medium modeling* allows for a fine-grained analysis of the state-of-the-art in emulation and real world testbeds. 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 1 summarizes our findings and provides a starting point for choosing of an appropriate testbed platform. Since development progresses at a rapid pace, we provide an extended version of this survey as a live document [15].

Future work includes the consolidation of individual testbed efforts. Testbeds such as **ORBIT** [27], **TrueMobile** [12], **Whynet** [30], and **Create-NET** [1] are shared among several research institutions and allow for large-scale experiments with a high emulation fidelity.

References

[1] I. Carreras, R. Grasso, C. Kiraly, S. Pera, H. Woesner, Y. Ye, and C. A. Szabo. Design Considerations on the CREATE-NET Testbed. In *Proceedings of 1st IEEE International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities (TRIDENTCOM 2005)*, pages 44–53, 23-25 February 2005.

[2] P. De, A. Raniwala, S. Sharma, and T. Chueh. MiNT: A Miniaturized Network Testbed for Mobile Wireless Research. In *Proceedings of IEEE 24th Annual Joint Conference on Computer and Communications Societies (INFOCOM 2005)*, pages 2731–2742, 13-17 March 2005.

[3] M. Engel, B. Freisleben, M. Smith, and S. Hanemann. Wireless Ad-Hoc Network Emulation Using Microkernel-Based Virtual Linux Systems. In *Proceedings of 5th EUROSIM Congress on Modeling and Simulation (EUROSIN 2005), Marne la Vallee, France*, pages 198–203, 6-10 September 2004.

[4] J. Flynn, H. Tewari, and D. O'Mahony. JEmu: A Real Time Emulation System for Mobile Ad Hoc Networks. In *Proceedings of the SCS Conference on Communication Networks and Distributed Systems Modeling and Simulation (CNDS 2002), San Antonio, Texas, USA*, pages 115–120, January 27-31 2002.

[5] E. Göktürk. Emulating Ad Hoc Networks: Differences from Simulations and Emulation Specific Problems. In *Proceedings of 20th International Symposium on Computer and Information Sciences (ISCIS 2005)*, pages 198–203, 26-28 October 2005.

[6] R. S. Gray, D. Kotz, C. Newport, N. Dubrovsky, A. Fiske, J. Liu, C. Masone, S. McGrath, and Y. Yuan. Outdoor Experimental Comparison of Four Ad hoc Routing Algorithms. In *Proceedings of 7th ACM International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM 2004), Venice, Italy*, pages 220–229, 4-6 October 2004.

[7] V. Guffens and G. Bastin. Running Virtualized Native Drivers in User Mode Linux. In *Proceedings of USENIX Annual Technical Conference (USENIX 2005)*, pages 33–40, 10-15 April 2005.

[8] R. He, M. Yuan, J. Hu, H. Zhang, Z. Kan, and J. Ma. A Real-time Scalable and Dynamical Test System for MANET. In *Proceedings of 14th IEEE Conference on Personal, Indoor and Mobile Radio Communications (PIMRC 2003), Beijing, China*, pages 1644–1648, 7-10 September 2003.

[9] E. Hernandez and A. S. Helal. RAMON: Rapid-mobility Network Emulator. In *Proceedings of IEEE 27th Annual Conference on Local Computer Networks (LCN 2002)*, pages 809–817, 6-8 November 2002.

[10] D. Herrscher, S. Maier, and K. Rothermel. Distributed Emulation of Shared Media Networks. In *Proceedings of the International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS 2003)*, pages 226–233, 20 July 2003.

[11] R. Jain. *The Art of Computer Systems Performance Analysis: Techniques for Experimental Design, Measurement, Simulation, and Modeling.* Wiley-Interscience, May 1991.

[12] D. Johnson, T. Stack, R. Fish, D. Flickinger, R. Ricci, and J. Lepreau. TrueMobile: A Mobile Robotic Wireless and Sensor Network Testbed. Technical Report FTN-2005-02, University of Utah Flux Group, April 2005.

[13] G. Judd and P. Steenkiste. Repeatable and Realistic Wireless Experimentation Through Physical Emulation. *ACM SIGCOMM Computer Communications Review*, 34(1):63–68, January 2004.

[14] J. T. Kaba and D. R. Raichle. Testbed on a Desktop: Strategies and Techniques to Support Multi-hop MANET Routing Protocol Development. In *Proceedings of the 2nd ACM international symposium on Mobile ad hoc networking & computing (MobiHoc 2001), Long Beach, CA, USA*, pages 164–172, 2001.

[15] M. Kropff, T. Krop, M. Hollick, P. S. Mogre, and R.Steinmetz. A Survey on Real World and Emulation Testbeds for Mobile Ad hoc Networks, 2006. Available at ftp://ftp.kom.tu-darmstadt.de/pub/papers/testbedsurvey.pdf.

[16] J. Lei, R. Yates, L. Greenstein, and H. Liu. Wireless link SNR Mapping Onto an Indoor Testbed. In *Proceedings of IEEE 1st International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities (TRIDENTCOM 2005)*, pages 130–135, 23-25 February 2005.

[17] T. Lin, S. F. Midkiff, and J. S. Park. A Dynamic Topology Switch for the Emulation of Wireless Mobile Ad Hoc Networks. In *Proceedings of the 27th Annual IEEE Conference on Local Computer Networks (LCN 2002), Washington, DC, USA*, pages 791–798, 6-8 November 2002.

[18] W. Liu and H. Song. Research and Implementation of Mobile Ad hoc Network Emulation System. In *Proceedings of 22nd International Conference on Distributed Computing Systems Workshops (ICDCSW 2002), Vienna, Austria*, pages 749–754, 2-5 July 2002.

[19] J. Macker, W. Chao, and J. Weston. A Low-cost, IP-based Mobile Network Emulator (MNE). In *Proceedings of IEEE Military Communications Conference (MILCOM 2003)*, pages 481–486, 13-16 October 2003.

[20] P. Mahadevan, A. Rodriguez, D. Becker, and A. Vahdat. MobiNet: A Scalable Emulation Infrastructure for Ad hoc and Wireless Networks. In *Proceedings of International Workshop on Wireless Traffic Measurements and Modeling (WiTMeMo 2005), Seattle, WA, USA*, pages 7–12, 5 June 2005.

[21] S. Maier, D. Herrscher, and K. Rothermel. On Node Virtualization for Scalable Network Emulation. In *Proceedings of International Symposium on Performance Evaluation of Computer and Telecommunication Systems (SPECTS 2005), Philadelphia, PA, USA*, pages 917–928, 25-29 July 2005.

[22] D. Maltz, J. Broch, and D. Johnson. Lessons From a Full-scale Multihop Wireless Ad hoc Network Testbed. *IEEE Personal Communication Magazine*, 8(1):8–15, February 2001.

[23] M. Matthes, H. Biehl, M. Lauer, and O. Drobnik. MASSIVE: An Emulation Environment for Mobile Ad-Hoc Networks. In *Proceedings of IEEE 2nd Annual Conference on Wireless On-demand Network Systems and Services (WONS 2005), St. Moritz, in Switzerland*, pages 54–59, 19-21 January 2005.

[24] E. Nordström, P. Gunningberg, and H. Lundgren. A Testbed and Methodology for Experimental Evaluation of Wireless Mobile Ad hoc Networks. In *Proceedings of 1st IEEE International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities (TRIDENTCOM 2005)*, pages 100–109, 23-25 February 2005.

[25] M. Puzar and T. Plagemann. NEMAN: A Network Emulator for Mobile Ad-Hoc Networks. In *Proceedings of 8th International Conference on Telecommunications (ConTEL 2005), Zagreb, Croatia*, 15 June 2005.

[26] R. Ramanathan and R. Hain. An Ad hoc Wireless Testbed for Scalable, Adaptive QoS Support. In *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC 2000)*, pages 998–1002, 23-28 September 2000.

[27] D. Raychaudhuri, I. Seskar, M. Ott, S. Ganu, K. Ramachandran, H. Kremo, R. Siracusa, H. Liuand, and M. Singh. Overview of the ORBIT Radio Grid Testbed for Evaluation of Next-generation Wireless Network Protocols. In *Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC 2005)*, pages 1664–1669, 13-17 March 2005.

[28] H. Ritter, M. Tian, T. Voigt, and J. Schiller. A Highly Flexible Testbed for Studies of Ad-hoc Network Behaviour. In *Proceedings of IEEE 28th Annual Conference on Local Computer Networks (LCN 2003)*, pages 746–752, 20-24 October 2003.

[29] S. Sanghaniand, T. X. Brownand, S. Bhandare, and S. Doshi. EWANT: The Emulated Wireless Ad hoc Network Testbed. In *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC 2003)*, pages 1844–1849, 16-20 March 2003.

[30] M. Takai, R. Bagrodia, M. Gerla, B. Daneshrad, M. Fitz, M. Belding-Royer, S. Krishnamurthy, M. Molle, P. Mohapatra, R. Rao, U. Mitra, C.-C. Shen, and J. Evans. Testbeds and Research Infrastructures for the Development of Networks and Communities. In *Proceedings of 1st IEEE International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities (TRIDENTCOM 2005)*, pages 162–171, 23-25 February 2005.

[31] Y. Zhang and W. Li. An Integrated Environment for Testing Mobile Ad-hoc Networks. In *Proceedings of 3rd ACM International Symposium on Mobile Ad hoc Networking & Computing (MobiHoc 2002), Lausanne, Switzerland*, pages 104–111, June 2002.

[32] P. Zheng and L. M. Ni. EMWIN: Emulating a Mobile Wireless Network Using a Wired Network. In *Proceedings of 5th ACM International Workshop on Wireless Mobile Multimedia (WoWMoM 2002), Atlanta, Georgia, USA*, pages 64–71, 28 September 2002.

[33] P. Zheng and L. M. Ni. EMPOWER: A Network Emulator for Wireline and Wireless Networks. In *Proceedings of 22. Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2003), San Francisco, California, USA*, pages 1933–1942, 30 March - 3 April 2003.

Table 1. Summary and Classification of Real World and Emulation Testbeds for MANETs.

Testbed	Architecture	Mobility Modeling	Wireless Medium Modeling	Virtuality	Reported Size
APE [24]	real world testbed, distributed control	real (person), logical connectivity	IEEE 802.11	1:1	37 physical
Ritter et al. [28]	real world testbed	real (person)	Bluetooth + 433/868 MHz RF module	1:1	5 physical
Maltz et al. [22]	real world testbed	real (person + vehicular)	IEEE 802.11	1:1	8 physical
DAWN [26]	real world testbed	real (person)	2.4 GHz ISM RF module	1:1	10 physical
Gray et al. [6]	real world testbed, distributed control	real (person), logical connectivity	IEEE 802.11	1:1	33 physical
MiNT [2]	real world testbed (miniaturized)	real (robots)	IEEE 802.11	1:1	8 physical
TrueMobile [12]	real world testbed (miniaturized)	real (robots)	900 MHz Mica2 mote + 802.11 control channel	1:1	16 physical
EWANT [29]	RF emulation	real (antenna switching)	IEEE 802.11	1:1	4 physical
Kaba et al. [14]	RF emulation	channel emulation	IEEE 802.11	1:1	4 physical
RAMON [9]	RF emulation	channel emulation	IEEE 802.11	1:1	1 physical
ORBIT [27]	RF emulation, centralized control	real (antenna switching)	IEEE 802.11 + Bluetooth + artifical interferer	1:1	400 physical
Judd et al. [13]	centralized control	channel emulation (digital baseband)	IEEE 802.11	1:1	3 physical (prototype)
JEMU [4]	centralized control	logical connectivity	on wired, centralized collision detection on frame level	1:1	12 physical
Lin et al. [17]	centralized control	logical connectivity	on wired, centralized bandwidth adaptation to IEEE 802.11	1:1	4 physical
MobiNet [20]	centralized control	logical connectivity	on wired, centralized physical, link, and routing layer emulation	m:n (hybrid)	200 virtual
MASSIVE [23]	distributed control	logical connectivity	on wired, no bandwidth adaptation	1:1	13 physical
MNE [19]	real world testbed, distributed control	real (person), logical connectivity	IEEE 802.11	1:1	10 physical
MobiEmu [31]	distributed control,	logical connectivity	on wired, no bandwidth adaptation	1:1, m:n (hybrid)	50 physical
EMWIN [32] / EMPOWER [33]	distributed control	logical connectivity	on wired, wireless MAC emulation	m:n (hybrid)	48 virtual
NET[10] [21]	distributed control	logical connectivity	on wired, distributed bandwidth adaptation, distributed MAC emulation	m:n (hybrid)	64 physical, 1920 virtual
NE [18]	distributed control	logical connectivity	on wired, distributed bandwidth adaptation	1:1	–
NEMAN [25]	centralized control	logical connectivity	intra node pointer passing	1:n (monol.)	1 physical
ManTS [8]	distributed control	logical connectivity	on wired, centralized bandwidth adaptation and MAC emulation	m:n (hybrid)	–
Engel et al. [3]	distributed control	logical connectivity	intra node pointer passing	m:n (hybrid)	5-10 virtual per physical