Used with permission.
The views expressed are those of the author and do not reflect the official policy or position of DARPA, the Department of Defense, or the U.S. Government.

Protocols: Strength in numbers through Design-in-the-Large

Ramakrishna Gummadi, Bryan Ford and Yang Richard Yang
Yale University

Li Erran Li
Bell Labs, Alcatel-Lucent

We witnessed a large rise in software and hardware developments on multiple wireless fronts in both theory and practice (software radios, cross-layer protocols, new practical directions in signal processing, communication and information theory). But large scale MANETs have not developed concomitantly. Inherent impediments such as handling unpredictable mobility in the absence of infrastructure, limited node capabilities, high interference and reduced radio resources, and difficulties in achieving scalable and reliable ad hoc routing are widely known from previous research [6]. Although researchers have addressed each of these specific problems to varying degrees of success [4], solutions treating multiple facets of this domain as a cohesive and deployable MANET architecture that scales gracefully to thousands of nodes are much rarer.

We propose to rethink MANET designs based on a radically new hypothesis: that it might actually be *easier* to design a MANET from the ground up for the case of a network with a large (>1000) number of nodes than for a smaller sized network, which forms the (convenient) starting point for current approaches. The key insight that lends credence to this hypothesis is that, unlike small wireless networks, whose scalability and reliability properties may be highly unpredictable, and topology- or deployment-specific, large scale networks can exhibit surprisingly simple yet robust emergent phenomena that are more amenable to design [1].

MANETs are especially suitable for amplifying the benefits of this "design in the large" philosophy: natural factors such as the ad-hoc nature, mobility and diversity that are traditionally considered impediments can sometimes be turned on their head to be assets instead. This novel possibility opens up due to several reasons that are either well-known in other fields such as statistics, statistical mechanics, and complex systems, or arise due to specific characteristics of MANETs. For e.g., the law of large numbers predicts reduced variance of undesirable phenomena such as unreachability and application-level failures across large population sizes. It is often simpler and useful to reason about the macroscopic aggregate properties of the entire system such as reachability to a portion of the network instead of node-specific routing state. Also, sudden phase-transitions can occur to reveal useful emergent phenomena about connectivity, routing and packet delivery rates as the size, mobility, or physical layer diversity of wireless networks increase, or when a modest amount of node hierarchy is introduced [2].

We outline the opportunities and challenges a new clean-slate architecture that integrates this "design in the large" principle into multiple aspects of MANETs. The key MANET properties that we embed our principle into are constrained resources; unpredictable channels; mobility; partially redundant many-to-many data patterns; and security and economic incentives:

1. **Large Antenna Systems.** Even small MIMO systems exploit diversity and harness capacity. Surprisingly, our recent hardware and algorithmic research on large-scale multi-user MIMO [5] suggests that it is possible to achieve simpler and more power efficient signal processing as node sizes and network diversities increase to hundreds of antennas and users. To exploit this opportunity, we will equip a subset of nodes with a large number of MIMO antenna arrays to facilitate a fraction of long range links in the network, in addition to many single-hop broadcast domains. Additionally, interesting challenges, such as increasing the supported physical coverage area in addition to node counts or node density, and network connectivity and management issues arise.
2. **Flexible resource allocation.** The ad hoc nature of MANETs open up the possibility of allocating radio resources such as transmit power, spectrum, and transmission times dynamically, according to the transient channel conditions experienced by nodes [7]. For large networks, additional resource allocation flexibility opens up because resources begin to exhibit statistical distributions, which means, for example, challenged nodes can be temporarily deallocated without impacting macroscopic network properties. It would be interesting to examine application-specific resource allocation as well.
3. **Exploiting heterogeneity and mobility.** By adding a small amount of heterogeneity to a large network, prior work suggests that it is possible to build a robust control plane that can withstand failures and exploit mobility [2] in some controlled network settings. Large-scale MANETs can potentially do better.
4. **Harnessing redundant and many-to-many transfers.** Here, we wish to extend recent research [3] to large MANETs by enabling more scalable data dissemination with application-specific modulation and multi-user decoding for multimedia.
5. **Incorporating robustness and security.** Our recent research into censorship-resistant communication shows that user-level diversity across space and time can be used to provide strong forms of security and privacy, and can withstand many otherwise stringent attacks [8]. Extending into large MANETs provides both opportunities and challenges for network effects and economic incentives to kick in.

Used with permission.
The views expressed are those of the author and do not reflect the official policy or position of DARPA, the Department of Defense, or the U.S. Government.

References

[1] *Scale-Free Networks: Complex Webs in Nature and Technology (Oxford Finance)*. Oxford University Press, USA, June 2007.

[2] David Kiyoshi Goldenberg, Jie Lin, A. Stephen Morse, Brad E. Rosen, and Y. Richard Yang. Towards mobility as a network control primitive. In *Proceedings of the 5th ACM international symposium on Mobile ad hoc networking and computing*, MobiHoc '04, pages 163–174, New York, NY, USA, 2004. ACM.

[3] Xiao Lin Liu, Wenjun Hu, Qifan Pu, Feng Wu, and Yongguang Zhang. Parcast: soft video delivery in mimo-ofdm wlans. In *Proceedings of the 18th annual international conference on Mobile computing and networking*, Mobicom '12, pages 233–244, New York, NY, USA, 2012. ACM.

[4] C. Perkins, E. Belding-Royer, and S. Das. Ad hoc on-demand distance vector (aodv) routing, 2003.

[5] Clayton Shepard, Hang Yu, Narendra Anand, Erran Li, Thomas Marzetta, Richard Yang, and Lin Zhong. Argos: practical many-antenna base stations. In *Proceedings of the 18th annual international conference on Mobile computing and networking*, Mobicom '12, pages 53–64, New York, NY, USA, 2012. ACM.

[6] Tanu Preet Singh, Dr. R.K Singh, and Jayant Vats. Article: Routing protocols in ad hoc networks: A review. *International Journal of Computer Applications*, 25(4):30–35, July 2011. Published by Foundation of Computer Science, New York, USA.

[7] David Tse and Pramod Viswanath. *Fundamentals of wireless communication*. Cambridge University Press, New York, NY, USA, 2005.

[8] David Isaac Wolinsky, Henry Corrigan-Gibbs, Bryan Ford, and Aaron Johnson. Strong, scalable anonymity in dissent. In *Proceedings of the Tenth USENIX Symposium on Operating Systems Design and Implementation (OSDI '12)*. USENIX Association, 2012.