ON HOW TO CIRCUMVENT THE MANET SCALABILITY CURSE

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I. INTRODUCTION

Research in the area of *Mobile Ad Hoc Networks* (*MANETs*) has focused in the past on two fundamental approaches: hierarchical networks (also referred to here as base-station-oriented networks) and flat networks (also referred to here as peer-to-peer networks). In base-station-oriented architectures, in contrast to flat networks, some mobile nodes are chosen to serve as base-stations; those nodes provide the function of "cluster heads." Routing in base-station-oriented networks is performed by forwarding packets to the closest base-station. From there, the packet travels to the base-station of the destination node. Typically, the base-station nodes might be equipped with additional or more advanced hardware, thus improving the communication and processing capabilities of those nodes. Such nodes may be satellite-, airborne- and/or terrestrially based, and their topology (links and switches) is dynamic. On the other hand, flat ad hoc networks (or "infrastructure-less" networks, as they are often called) are wireless networks that typically consist of nodes, all of which perform similar functionality. In such networks, every node functions as a router and routing is done without the constraint of the path passing through any particular node or nodes. The two types of networks differ fundamentally in their architectures and in the expected scalability [1, 2, 3].

Since the publication of the Gupta and Kumar paper [4] in March 2000, it has been accepted in the research community that building very large ad hoc networks (MANET) is a challenge; although the total throughput of a flat-routed network increases with the number of nodes, the per-connection end-to-end throughput decreases. In the limit, the per-connection end-to-end throughput approaches 0. Furthermore, the standard engineering approach hierarchical networks (i.e., that of "divide and conquer"), where the network nodes are partitioned into clusters, and where the communication among clusters is conducted through a high-tier network, does not resolve the vanishing end-to-end throughput either. In other words, fundamentally, both types of ad hoc networks, the hierarchical and the flat architectures, are inherently non-scalable. It seems that given some communication spectrum, and at some values of communication parameters, to achieve useful end-to-end throughput, one is required to keep the number of nodes below some level. The ugly face of the scalability curse shows up!

In this paper, we introduce our approach to circumventing this scalability curse. Our approach, similar to the hierarchical ad hoc networks, is based on a two-tiered architecture, in which the lower tier comprises of "clouds" of flat ad hoc networks based on standard diffused RF technology. In each one of the lower tier networks, there is at least one node which serves as a base station and which, in addition to being able to interface the other nodes through the omni-directional RF technology, is also interconnected by directional wireless backbone links to other base-station nodes. This higher-tier network would typically use a hybrid of *Free Space Optics (FSO)* and directional *RF* technologies, referred to here as *FSO/RF*, both of which can operate up to Gbs; FSO using near-infrared laser beams and the RF channel operating in the millimeter wave region. Integration of these two complementary technologies allows us to scale the network to very large sizes (in the number of nodes), effectively circumventing the scalability curse.

In particular, the results of our work teach us how the lower-tier, RF-based MANET could be grown to large sizes (i.e., number of nodes), while preventing the per node end-to-end throughput to vanish. To achieve this, ***the network area needs to grow along with the increase in the number of nodes, and such a growth in the area needs to follow specific patterns,*** which we have derived in our work. However, in practical situations, the network area cannot grow without bound. Thus, the high data rate, *directional wireless (FSO/RF)* technology in the higher-tier backbone which, relying on spatial reuse, allows us to

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practically indefinitely increase the size of the network, without affecting its end-to-end performance.

The main rationale behind integration of low tier peer-to-peer RF network with the higher tier FSO/RF network stems from the fact that the two technologies are **complementary** in their features and in their attributes. In fact, the particular requirements of the lower tier network are well satisfied by the RF technology, while the particular constraints of the higher tier network well match the FSO/RF technology.

II. THE RATIONALE BEHIND THE TWO-TIERED RF&FSO/RF ARCHITECTURE

Figure 1 presents the concept of two-tiered integrated RF and FSO/RF architecture. Then main rationale behind integration of the low tier peer-to-peer RF network with the higher tier peer-to-peer FSO/RF network stems from the fact that the two technologies are complementary**.** The complementary nature of the two technologies allows us to exploit the attributes of each one of the technologies to compensate for the other. In other words, the particular requirements of the lower-tier network are well satisfied by the RF technology, while the particular constraints of the higher-tier network well match the FSO/RF technology.

The following table summarizes some of the main attributes of the two technologies. The values in the column "Attributes" in this table should be interpreted as "requirements," while the values in the "*Diffused RF*" and the *"Free-Space Optics"* columns should be construed as what these technologies can offer.

Attribute	***FSO/RF (higher tier)***	***Diffused RF (lower tier)***
Transmission Distance	Large transmission distance	Relatively small transmission distance
Throughput	Large aggregated throughput	Relatively small throughput
Topology Stability	Relatively stable topology	High reconfiguration rate
Number of nodes	Small number of nodes	Massive number of nodes
Connectivity	High connectivity	Relatively lower connectivity

For instance, there are significantly more nodes on the lower tier of the network, and the nodes can be characterized by having relatively higher mobility and lower throughput requirements,[1] as compared with the

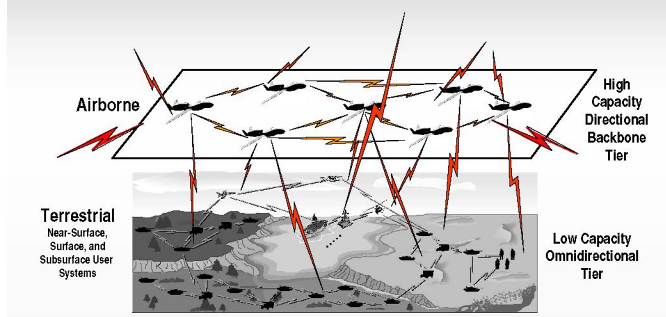

Fig. 1: Scalable, Hybrid, Two-Tiered Battlespace Network

base-station nodes. Thus low transmission power, low throughput, and omni-directional links created by the RF technology are sufficient to satisfy these requirements. On the other hand, the higher tier is created by a relatively small number of relatively more stable nodes, that aggregate traffic carried between clusters and that covers larger distances, and is thus better implemented through the FSO/RF technology. The FSO/RF technology provides a substantially larger bandwidth, is more suitable for less frequent topological reconfiguration, and allows to operate links over significantly larger distances due to the fact that the FSO/RF transmission is more directional that omni-directional RF.

There are other reasons why the use of the RF&FSO/RF hybrid is so much more appropriate for military networks, with the special needs of such a communication environment as a battlefield is. In the interest of space, we omit further discussion of these issues, just noticing that the nature of the traffic in military applications is another supportive factor in the choice of the RF&FSO/RF hybrid.

III. SCALABILITY OF THE TWO-TIERED ARCHITECTURE

III.A. Prior Results

Undoubtedly, the publication of the capacity results by Gupta and Kumar in [4, 6, 13] has stimulated the scientific community to search for a better understanding of what are, indeed, the scalability bounds of wireless networks. In [4], a theoretical framework to analyze the capacity of peer-to-peer wireless networks was formalized through two network models. The first network model, the *arbitrary network* model, assumes that all N nodes in

[1] Since the nodes on the lower tier carry and relay traffic for a smaller number of nodes than the nodes on the higher tier.

the network are static, there are no restrictions on node locations, and the network domain (i.e., the region within which the nodes are located) is a circular disk of a given area. At any given time, each node is capable of maintaining at most one omnidirectional transmission or one omnidirectional reception. There are no restrictions on the choice of the transmission powers, the traffic pattern, the routing protocol, and the spatial-temporal transmission scheduling policy. The second model is the *random network* model, which assumes a uniform distribution of node locations, a random traffic pattern, and a fixed transmission power that is selected to ensure the connectivity of the network as N becomes large.

Additionally, in [4], two models for successful reception are proposed. The first reception model is the *protocol model*, which considers a transmission as unsuccessful if the receiver is within the interfering range of an unintended transmitter. The second model is the *physical model*, which better represents realistic reception in practical wireless networks. In the physical model, the Signal-to-Interference-and-Noise Ratio, *SINR*, at a receiver has to be above a threshold value for the transmission to be successful. It is assumed that P/x^{γ} is the power received at a distance x from a transmitter, where P is the transmitted power, and the path loss exponent γ is assumed to be larger than 2.

The conclusions of [4] are as follows: With the protocol model, λ_e is $O(1/\sqrt{N})$ for arbitrary networks, and $O(1/\sqrt{N\log(N)})$ for random networks. With the physical model, they concluded that λ_e is $O(1/N^{1/\gamma})$ and $\Omega(1/\sqrt{N})$ for arbitrary networks, whereas, λ_e is $O(1/\sqrt{N})$ and $\Omega\left(1/\sqrt{N\log(N)}\right)$ for random networks.

One of the limitations of [4] is the requirement that all nodes are immobile. In [15], Grossglauser and Tse explored whether or not introducing mobility can increase λ_e. Their network model has some additional restrictions on the random network model of [4]. Firstly, they used the physical model, but allowed wideband communication by incorporating the processing gain, as to reduce interference. Secondly, the nodes are mobile and their locations form a stationary ergodic process with a uniform stationary distribution in the network domain. Thirdly, source-destination pairs do not change. Finally, they assumed that very long end-to-end packet delays are tolerable. They concluded that there exists a routing and scheduling policy that delivers a packet to its destination with no more than two hops, and allows λ_e to be $\Theta(1)$ as N becomes large.

In [6], Gupta and Kumar extended their results to a spherical network domain. They concluded that, with the protocol model λ_e is $O(1/N^{1/3})$ for arbitrary networks, and $O(1/[N\log^2(N)]^{1/3})$ for random networks. With the physical model, assuming $\gamma > 3$, they concluded that λ_e is $O(1/N^{1/\gamma})$ and $\Omega(1/N^{1/3})$ for arbitrary networks, whereas, λ_e is $O(1/N^{1/3})$ and $\Omega(1/[N\log^2(N)]^{1/3})$ for random networks.

In [7], Diggavi, Grossglauser and Tse extended the results of [15] to a one dimensional mobility pattern, and concluded that the asymptotic results of [15] continue to hold. The previous works concluded that it is possible to schedule $O(N)$ many simultaneously successful transmissions in a wireless network.

In [8], Toumpis and Goldsmith numerically evaluated the effect of spatial reuse, multi-hop routing, power control, and successive interference cancellation for a particular placement of nodes. In [9], Li et al. concluded that only wireless networks with local traffic patterns can be scalable. In [10], Yi, Pei, and Kalyanaraman evaluated the improvement in λ_e that can be provided by the usage of directional antennas for arbitrary and random wireless networks. In [11], using directional antennas, Peraki and Servetto studied the improvement in λ_e for random networks with and without multiple simultaneous transmission or reception capability. In [12], Liu, Liu and Towsley considered the benefit of deploying base stations connected to a wired backbone in the random network of [4]. On the other hand, there have also been information theoretical approaches such as [13] and [14].

Our work has been motivated by the desire to relax some of the limitations of [4]-[7] and to improve on their models. In particular, the radio propagation model (P/x^{γ}), which has been widely used in such studies, becomes invalid as the transmitter-receiver separation becomes small. Hence, the model gives unrealistic, and thus unreliable, results when the nodal density increases beyond some limit. In terms of mobility, in [4] and [6] nodes are immobile, while in [15] and [7] the mobility pattern is a very special one – we allow for a general mobility pattern of the nodes. Furthermore, we relax the assumptions in [15] and [7] that the source-destination pairs never change, and that the end-to-end packet delays can be unbounded. Moreover, in [4]-[7] each node can maintain either a single transmission or reception at a given time, whereas we also consider the situtation when the nodes can maintain multiple simultaneous transmissions and/or receptions. Above all, we analyze the dependency of λ_e on parameters other than N, such as D, γ, G and β, none of which has been addressed in [4]-[14].

The main contribution of our study has been in the derivation of a new approach to analyze the ***scalability*** and ***growability*** patterns of wireless networks through the use of a more general network model as compared with the network models of previous studies.

III.A. Extending the Prior Results

In our work, we have studied the capacity of wireless networks with a more general network model than the models used in [4]-[7], and determined the implications of our results on scalability. We consider a wireless network of N nodes that are equipped with isotropic antennas. The nodes are located in a *dim* dimensional network domain Q that has an arbitrary shape and diameter D. With a unified treatment of each of the three dimensions, we obtained upper bounds on N_t^Q, $N_t^{\max}$, λ_e and λ_m. In particular, we derived bounds on the maximum number of simultaneously successful wireless transmissions, $N_t^{\max}$, and the per node end-to-end throughput capacity, λ_e, under a more general network scenario than the network scenarios of previous works. Throughout our work, we put no restrictions on the mobility pattern of the nodes, and allowed the nodes to maintain multiple simultaneous transmissions and/or receptions. We also analyzed the dependencies of λ_e and $N_t^{\max}$ on parameters such as N, D, the path loss exponent γ, the processing gain G, and the $SINR$ threshold β.

In contrast with [4]-[7], which used the conventional propagation model, and concluded that $N_t^{\max}$ is $\Theta(N)$, we showed that, even with the general propagation model, $N_t^{\max}$ has an upper bound that does not depend on N. We named this special quantity as the simultaneous transmission capacity of the network domain, and denoted it by N_t^Q.

As an alternative to the propagation model used in [4]-[7], we used a realization of the general propagation model, called the power law decaying propagation model, which was proposed in other studies such as [17] and [18] to obtain more meaningful results for small transmitter-receiver distances, while approximating the conventional model at large distances. With this model, we showed that N_t^Q is $O(D^{\min\{\gamma, dim\}})$ if $\gamma \neq dim$ and $O(D^{dim}/\log(D))$ if $\gamma = dim$. Our analysis has also shown that N_t^Q is $O(\gamma^{dim})$ and $O(G/\beta)$.

Additionally, since the network model that we have used is more general than the models used in [4]-[7], the results presented in this paper do not only hold for the network scenarios of [4]-[7], but also hold for networks whose nodes move with any mobility pattern or are capable of maintaining any number of simultaneous transmissions and/or receptions. Hence, we have been able to show that maximum achievable per node end-to-end throughput is $O(1/N)$ and $O(1/\overline{H})$, even when the mobility pattern of the nodes, the spatial-temporal transmission scheduling policy, the temporal variation of transmission powers, the source-destination pairs, and the possibly multi-path routes between them are optimally chosen. Furthermore, the results hold even when the nodes are capable of maintaining multiple transmissions and/or receptions simultaneously, or the communication bandwidth is divided into sub-channels of smaller bandwidth.

Moreover, the results of [4]-[7] are limited to values of γ that exceed the dimension of their network domains, whereas our results are valid for any nonnegative value of γ. This allowed us to show that lack of attenuation and lack of space are equivalent, where $N_t^{\max}$ and N_t^Q cannot exceed $1+G/\beta$. It further allowed us to show that λ_e and λ_m cannot exceed $W_{\max}(1+G/\beta)/(\overline{H}N)$ in these equivalent cases.

We have also shown that regardless of the propagation model and the structure of transmitter antennas, no node can receive more than $1+G/\beta$ simultaneously successful transmissions intended for itself. This allowed us to show that $N_t^{\max}$, λ_e and λ_m are $O(1)$ with respect to D and γ for a given N. This also allowed us to justify that the limitation of λ_e and λ_m due to shortage of space and attenuation is more pronounced when N is large.

Finally, with the power law decaying propagation model, we considered the implications of our results on the scalability patterns of wireless networks. We have shown that, as N becomes large, unless one or more of the parameters from $W_{\max}$, γ, G/β and D grows with N, and $\overline{H}N$ is $O(W_{\max}U_\gamma)$, a desired per node end-to-end throughput is not achievable. Regarding scalability of practical systems, we have concluded that $\overline{H}$ must be $\Theta(1)$ with respect to N. Moreover, we have concluded that D is the only feasible parameter whose growth can compensate for increasing N. Above all, we have proved that as $N\rightarrow\infty$, a desired per node end-to-end throughput is not achievable, unless D also grows with N, and N is $O(D^{\min\{\gamma, dim\}})$ when $\gamma \neq dim$ and is $O(D^{dim}/\log(D))$ when $\gamma = dim$.

To summarize our results, with a general propagation model and with a realization of it, called the "power law decaying propagation model," we proved the following four results:

1. With both propagation models, $N_t^{\max}$ has an upper bound that does not depend on N. The upper bound is the simultaneous transmission capacity of the network domain, N_t^Q. With both models, N_t^Q is $O(G/\beta)$. Moreover, with the power law decaying propagation model, N_t^Q is $O(D^{\min\{\gamma,dim\}})$ if $\gamma \neq dim$ and $O(D^{dim}/\log(D))$ if $\gamma = dim$. Also, N_t^Q is $O(\gamma^{dim})$.
2. With both propagation models, lack of attenuation and lack of space are equivalent, where N_t^Q cannot exceed $1+G/\beta$.
3. With both propagation models, λ_e is $O(1/N)$ even when the mobility pattern of the nodes, the spatial-temporal transmission scheduling policy, the temporal variation of transmission powers, the source-destination pairs, and the possibly multi-path routes between them are optimally chosen. This result continues to hold even when the nodes are capable of maintaining multiple transmissions and/or receptions simultaneously or the communication bandwidth is divided into sub-channels of smaller bandwidth. Moreover, regardless of the propagation model and the structure of transmitter antennas, λ_e is $O(1/\overline{H})$, where $\overline{H}$ is the average number of hops between a source and a destination.
4. Regarding scalability of practical systems, a desired per node end-to-end throughput is not achievable as N tends to infinity, unless the following conditions apply: $\overline{H}$ does not grow indefinitely with N, D also grows with N, and N is $O(D^{\min\{\gamma,dim\}})$ if $\gamma \neq dim$ and $O(D^{dim}/\log(D))$ if $\gamma = dim$. We term this growability pattern the ***Scalable Density Pattern (SDP).*** Figs. 2, 3, and 4 illustrate some of the results obtained in our work. For additional results, the reader is referred to [24]-[27].

IV. *FSO/RF* – The Ultimate Weapon Against the Scalability Curse

The results of our Information Theoretical work presented above (and the result (4), in particular) teach us how RF-based MANET could be grown to large sizes (i.e., number of nodes), while preventing the per node end-to-end throughput to vanish. To achieve this, ***the network area needs to grow along with the increase in the number of nodes, and such a growth in the area needs to follow specific patterns,*** which we have described above; i.e., the *Scalable Density Pattern (SDP).*

Do these Information Theoretical results suffice to completely address the problem of MANET scalability? Hardly, since the nodes do not need to follow the *SDP.* If this is the case, we then advocate the ***two-tiered approach.*** In this approach, the maximal size of any *cluster* of MANET nodes is determined by the required per node end-to-end capacity, in addition to the operational conditions of the network. Those clusters then constitute the lower tier RF networks and are interconnected by the higher tier, high capacity, spatially reused FSO/RF interconnects. The higher tier is created by allowing some nodes in the network to be equipped with two interfaces: the RF interface over which these nodes communicate with other nodes around them, and the FSO/RF interface, over which the communication with other higher tiers is established. Note that <u>both</u> of the tiers implement peer-to-peer, multi-hop communication. We refer to these two-interface nodes as *base stations;* however it is important to note that these base station nodes can be <u>mobile</u>, as any other

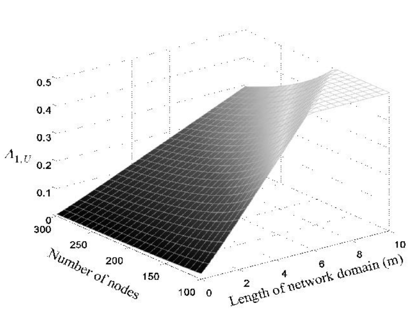

Fig. 2: Upper bound on λ_e and λ_m for a linear network domain.

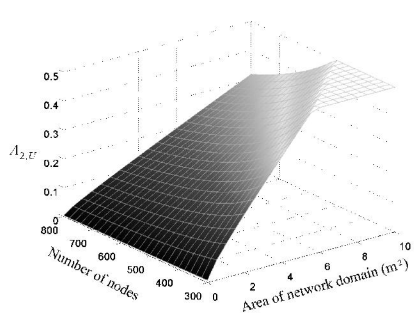

Fig. 3: Upper bound on λ_e and λ_m for a circular network domain.

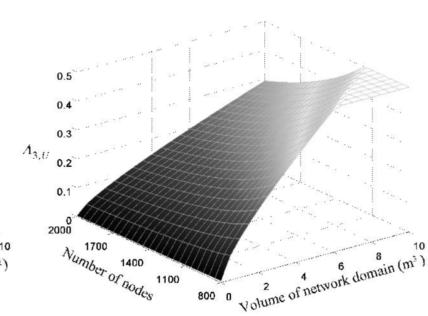

Fig. 4: Upper bound on λ_e and λ_m for a spherical network domain.

node in the network. In fact, the only difference between the mobile base station nodes and any other node in the network is in the ability of the base stations to communicate over both tiers.

It is important to realize that any node in the network can, in principle, become an active mobile base station node, if it is equipped with both interfaces. In other words, one possible realization of this architecture is that every node in the network is equipped with both interfaces and that at any time, some subset of those nodes become active base stations. The choice of which node becomes an active base station is determined in a distributed *Topology Control Algorithm (TCA).* Due to space limitation, we omit here the detailed description of the *TCA.* However, we note that the choice of which node become active mobile base stations at any time, as well as the total number of such base station is determined (distributively) in such a manner as to best approximate the *Scalable Density Pattern (SDP).*

In addition to the network construction algorithms for both the tiers, for the networks to operate, there is also the need for routing mechanisms; i.e., the functions of route discovery, forwarding, and secure routing need to be implemented. We have considered those mechanisms and came up with efficient (and effective) protocols that leverage from the particular characteristics of the two tiers. We will omit the details of those protocols, only to mention that Appendices F, G, and H, provide some insight into how these functions could be implemented for the higher tier FSO/RF network.

Furthermore, it is envisioned that some node may be more stable (reduced mobility relative to their surrounding neighborhood) than other nodes. In general, choice of such stable node to serve as the active base stations results in less frequent topological changes. Again, we skip the details here due to space limitation.

V. CONCLUSIONS

We have offered an approach to resolving the fundamental non-scalability of peer-to-peer, MANET networks by introducing ultra-broadband (up to and beyond 1Gb/s), hybrid (FSO/RF) directional backbone nodes that significantly increase the end-to-end throughput of lower tier nodes [19]-[22]. We believe that this approach represents a very different thrust from those which attempt to circumvent the limitations of low data rate (up to 54Mb/s) and short distance (hundreds of feet) MANET nodes by software fixes such as power control, MIMO, and clever modulation schemes, which are at best stop-gap measures.

Our two-tiered approach is scalable based on its combination of MANET clusters interconnected with very broadband directional connections. The MANET clusters are operated within the scalability limits set by *Scalability Density Pattern,* and the base-station oriented directional connections use very narrow beams to provide massive spatial re-use.

VI. APPENDIX

Scalability of Directional Links

The beam divergence half angle for an antenna of aperture D is:

$$\theta_B = \frac{1.22\lambda}{D}.$$

So directional links have a smaller beam angle as the antenna or frequency of the link is increased. FSO links can have much smaller beam angles, typically ranging from 1μrad to 10mrad. The beam angle of an FSO link is:

$$\theta_B = \frac{\lambda}{\pi w_0},$$

where w_0 is a Gaussian beam radius. Consequently for all directional links we can use an effective beam half angle:

$$\theta_B \approx \frac{\lambda}{D},$$

which allows us to write a universal figure of merit for links of half angle θ_B as

$$F = \frac{2\Delta f}{\left(1-\cos(\lambda/D)\right)V}.$$

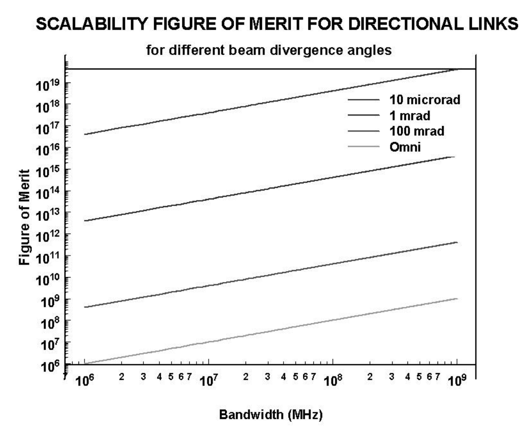

Figure 9: The figure of merit for narrow beam links

This figure of merit is shown for various scenarios in Figure 9.

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