On the Design of Self-Organized Cellular Wireless Networks

Sudhir Dixit, Evşen Yanmaz, and Ozan K. Tonguz

ABSTRACT

It has been observed that complex networks such as the Internet, World Wide Web, social networks, and biological systems are self-organizing in nature and exhibit some common properties such as the power law degree distribution. Recently, two models (i.e., small world and scale-free network models) have been proposed and successfully used to describe the nature of such networks. In this article we investigate whether these concepts can also be applied to cellular wireless networks, which typically do not exhibit self-organizing or scalability properties due to the limited range of the wireless nodes. Our ultimate goal is to design robust, reliable, scalable, and efficiently utilized wireless networks via self-organizing mechanisms.

INTRODUCTION

The size and scope of wireless networks continue to grow with more users, and introduction of a myriad of devices and sensors at homes and businesses. All this, in conjunction with short and dynamic flows of information, is adding to the spatiotemporal complexity of the network topology and dynamics requiring self-organization.

For over a century (until the late 1950s), physical systems were modeled assuming that interactions among the nodes in a system can be represented by a regular and perhaps universal structure of Euclidean lattices. In the 1950s Erdös and Rényi (ER) represented complex network topologies by random graphs [1], laying the foundation of random network theory. Until the late 1990s, random graph or network theory remained the only rigorous approach to studying complex networks. However, it has been observed that both of these approaches have some shortcomings and fail to represent some important properties of complex networks such as the Internet, which are not completely regular or random. Recently, with the availability and analyses of volumes of traces and statistics on the behavior of nodes, two major approaches to describe complex networks have been proposed: the *small world* [2, 3] and *scale-free* [4–7] concepts. Small world refers to a phenomenon where the average path length between nodes is small, the nodes are highly clustered, and the connectivity distribution peaks at an average value, then decays exponentially. Scale-free, on the other hand, means that the connectivity distributions can be represented by power-law form, which is independent of the size or scale of the network. Today, scale-free concepts are already being used to explain the Internet, the Web, and airline networks [1]. It is observed that complex networks self-organize themselves into a scale-free state [5].

In this article we explore the applicability of the small world and scale-free network concepts to cellular wireless networks. With the introduction of several wireless applications and demand for high data rates, it is anticipated that infrastructureless, easily deployable, wireless relay stations will be used in addition to the cellular infrastructure to improve service to mobile users. To this end, the system under investigation is a joint cellular and fixed relay node (FRN) network [8, 9] that makes use of the existing cellular infrastructure (i.e., the base stations and/or access points). Additional FRNs can be placed over geographical areas that may already be covered by base stations (BSs) to achieve load balancing, or over areas that are not covered by any BSs to extend the coverage of the BSs and provide Internet connection to the mobile users in rural areas. In this article our objective is to design a scale-free overlay FRN network for quality of service (QoS) purposes.

To do this, instead of trying to achieve scalability in a given network topology via routing and so on, we take a different approach, and try to create a topology that is "scale-free"; to this end, we make use of the small world and scale-free topology generation algorithms that were proposed for wired networks. We decompose the self-organization problem into two parts: topology generation and routing. Since scale-free is a property exhibited by self-organized networks such as the Internet, we first design the overlay infrastructureless FRN network with a scale-free physical topology, such that the average path length between the FRNs and BSs is small, and we show that "small wireless worlds" can be achieved under certain conditions. Once the FRNs are placed in a

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scale-free topology, a routing mechanism between the FRNs and BSs will be used such that the joint wireless network is self-organized into a load-balanced state. This mechanism is also expected to provide additional robustness to the cellular network (e.g., when a BS fails, the traffic destined to that BS can be rerouted to other BSs via FRNs).

THE SMALL WORLD AND SCALE-FREE NETWORK CONCEPTS

In this section, we briefly explain the small world and scale-free concepts. For details of these concepts, the readers are referred to several good references [2–7]. First, we would like to define some important parameters used to characterize complex networks.

Average path length (L) is defined as the average number of hops (edges) in the shortest path between two nodes, averaged over all node pairs in the network.

Clustering coefficient (C) is defined as the average fraction of pairs of neighbors of a node that are also neighbors of each other, calculated over the whole network.

Degree (k) of a node is defined as the number of links connecting that node to the neighboring nodes, and *average degree* is defined as the average of this over the whole network.

Recall that complex networks (e.g., the Internet, airline networks) exhibit small average path length, high clustering coefficient, and power-law degree distribution, and neither regular nor random graphs can be used to represent all these properties. Hence, the following concepts aim to capture these properties of the complex networks.

THE SMALL WORLD CONCEPT

Basically, in a small world the average path length is small (i.e., most nodes are a few hops away from each other) and the clustering coefficient is high. To form the small world model, Watts and Strogatz interpolated between a regular lattice and a random graph [2]. It is shown that randomly rewiring a few edges (i.e., removing a few edges and adding new edges to randomly selected nodes) reduces the average distance between nodes, but has little effect on the clustering coefficient. For both the random and small world models, the degree distribution (i.e., the number of neighbors of the nodes in the network) is exponential (i.e., probability of having k neighbors decreases exponentially with k). Hence, nodes with high connectivity are practically absent, and the power-law property is not observed.

As an illustration, the random rewiring procedure for interpolating between a regular ring and a random network is shown in Fig. 1. We assume that the number of nodes in the network is 20, and each node has an initial degree of 4. Here p is defined as the rewiring probability, where $p = 0$ and $p = 1$ represent the cases for regular and random graphs, respectively. Note that the average degree of the nodes after random rewiring is still 4.

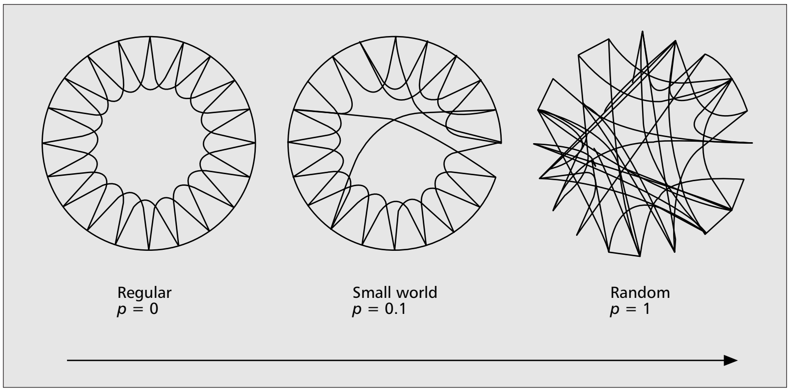

Figure 1. *Random rewiring procedure, such that randomness increases with the value* p.

Figure 2 shows the normalized average path length $[L(p)/L(0)]$ and clustering coefficient $[C(p)/C(0)]$ for a 1000-node network with an average degree of 10 for several rewiring probabilities. Observe that with a small rewiring probability (e.g., $p = 0.01$) small average path lengths and high clustering coefficients (exhibited in real complex networks) can be obtained.

SCALE-FREE NETWORKS

Recently, it has been observed that most large networks display scale-free features (i.e., their degree distributions are in power-law form), where most nodes have very few connections, and a few nodes (called *hubs*) have many connections [1]. Therefore, random graph or small world models (which exhibit an exponential degree distribution) do not capture this property of real networks. Barabási *et al.* used the following features of real networks to develop a scale-free network model:

- Real networks expand continuously by the addition of new nodes.
- New nodes attach *preferentially* to nodes that are already well connected.

These two properties (growth and preferential attachment) of the real networks lead to the scale-free property, and Barabási *et al.* show that both these properties have important roles for the power-law degree distribution [4–7]. However, Barabási *et al.* do not consider the effect of the removal of nodes and links on degree distribution, the study of which is an interesting research topic in and of itself [1].

The scale-free network model proposed by Barabási and Albert (BA) is formed by starting with a small number of (m_0) nodes, and at each time step adding a new node with m ($\leq m_0$) edges that is connected to the nodes already present in the system [4–7]. When choosing the nodes to which the new node connects, it is assumed that the probability that a new node will be connected to a node depends on the connectivity (degree) of that node. This model has been shown to have a power-law degree distribution. The BA model as described in this article is the basic minimum model and has limitations in modeling some real-world networks. Therefore, a number of enhancements to this model have recently been proposed [7].

To verify scale-free network generation using the BA model, the connectivity distribution of a growing network is studied. As an example, Fig. 3 shows the node and link addition procedure for $m_0 = 3$ and $m = 2$. A new node gets connected to an already existing node with a rate proportional to the degree of the corresponding node.

Next, we ran the above procedure until over 4000 nodes were added, starting with $m_0 = 3$ nodes. The degree distribution for this case is shown in Fig. 4. Observe that the degree distribution [$P(k)$] exhibits the power-law property, with the power exponent of -2.6 ± 0.3 for this case.

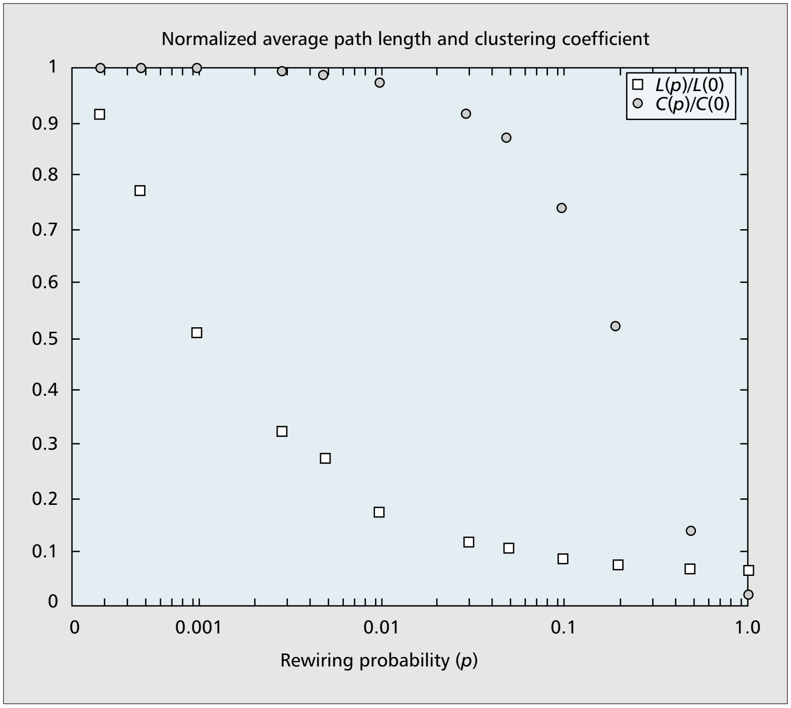

Figure 2. *Normalized average path length [L(p)/L(0)] and clustering coefficient [C(p)/C(0)] vs. rewiring probability (p).*

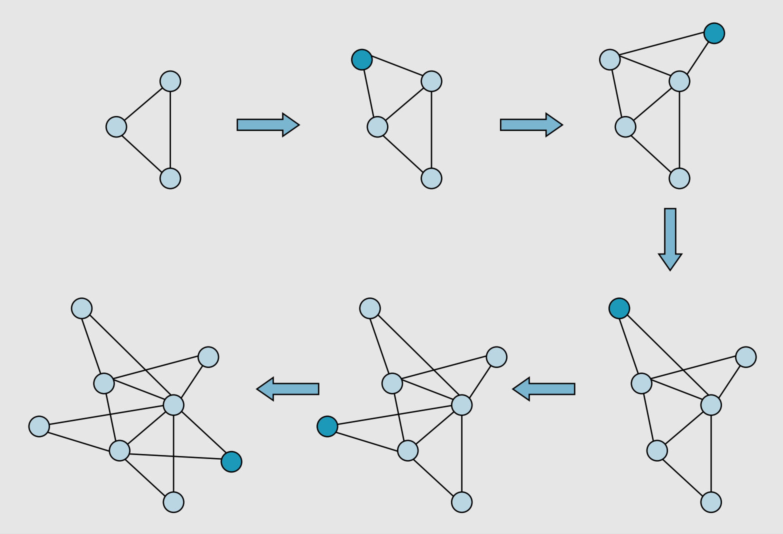

Figure 3. *Growth and preferential attachment procedure from three nodes to eight nodes, where new and existing nodes are shown in dark and light colors, respectively.*

APPLICATION OF SMALL WORLD AND SCALE-FREE MODELS TO CELLULAR WIRELESS NETWORKS

Although much work has been done in ad hoc wireless networking on the topics of self-configuration and multihop routing [10], the scalability of a hybrid network, which combines the cellular network and ad hoc wireless networks (i.e., relay-based networks) has not been studied before. Most previous work has studied ad hoc wireless networks that consist of mobile nodes placed randomly in the network, trying to achieve scalable routing protocols for such networks (e.g., hierarchical state routing [HSR] [11] and zone routing protocol [ZRP] [12]). In addition, a recent approach that applies small world model ideas to ad hoc wireless networks is proposed by Helmy [13, 14]. It is shown that by removing/adding (i.e., "rewiring") some wireless links randomly, small world effects can be obtained in wireless ad hoc and sensor networks. The removal/addition of links is implemented using physical wires between sensor nodes. However, we believe that introducing new links using physical wires is not realistic in wireless networks. Therefore, in our work we do not make this assumption, but attempt to make the network small-world-like. Another recently proposed approach that applies the small world concept to the application layer of the ad hoc networks is described in [15].

In this article we take a different approach, and instead of trying to achieve scalability in wireless networks for a given network topology by routing or using physical wires between randomly selected nodes, we try to generate a topology such that the resulting network is "scale-free." We consider overlay ad hoc wireless networks with a centralized controller (i.e., a BS). In the following we introduce the system under investigation, and show if and how a *small wireless world* can be achieved. A brief overview of this study was presented in [16].

THE SYSTEM MODEL

Traditional cellular wireless networks consist of BSs (or access points) controlled by a mobile switching center (MSC) that communicate over single-hop wireless links. We envision that in the future, in addition to the wireless infrastructure (i.e., the BSs), overlay fixed relay networks with no infrastructure can be deployed in the geographical coverage area to provide service to mobile users, enhance network performance, and use system resources (i.e., frequency channels) efficiently. Therefore, in this article we study a joint cellular and FRN network such as the integrated cellular and ad hoc relay (iCAR) system proposed in [8, 9]. We assume that an FRN is a wireless communication device that can communicate directly with a mobile user (MU), a BS, or another FRN via different air interfaces. We also assume that FRNs can operate in either the cellular band or unlicensed bands (e.g., the 2.4 GHz industrial, scientific, and medical [ISM] band) and hence have a limited number of channels. It has been shown that FRNs can be used to achieve dynamic load balancing among BSs, and improve the call blocking and dropping performance in cellular networks [8, 9]. Thus, the FRNs can provide robustness and traffic management features to the existing network (e.g., when a BS fails or is congested, the traffic destined to this BS can be rerouted to other BSs via FRNs). The FRNs can also be used to connect mobile nodes that are not covered by any BSs to the Internet at low cost and relay the traffic on demand.

In this article, unlike ad hoc wireless networks [10], we assume that the overlay FRN network is not mobile, but the users are mobile and can connect with any FRN. An example relay-based network is shown in Fig. 5. Observe that mobile users not covered by a BS can connect to a BS through FRNs over multiple hops.

THE APPROACH

In this section we investigate if and how the small world and scale-free network concepts can be created in cellular wireless networks so that they become scalable (e.g., average number of hops between node pairs is minimized). Here, node pairs consist of a BS and an FRN. We assume that the FRNs basically receive the signal of various mobile users and other FRNs (within their range), and transmit the received data to the next FRN or BS in the route. The FRNs do not have any (wired) infrastructure. Since connectivity between a mobile device and an FRN is single hop and an FRN functions as an aggregator and a traffic forwarder/router, we do not call the mobile terminal a node from the standpoint of the graph formulation.

Since multihop wireless networks belong to the class of spatial graphs, where the links between nodes depend on the radio range, it is clear that the small world and scale-free network concepts are not readily applicable. For example, the rewiring concept in the small world model or preferential attachment in the BA algorithm cannot be directly implemented in wireless networks. We therefore formulate our problem as designing an overlay wireless network that exhibits scale-free characteristics and self-organizes itself into a load-balanced state, and modify the aforementioned models to meet this objective.

There are basically two levels of organization, one at the physical reachability/connectivity level and the other at the logical packet routing level. Topology generation is relatively static, whereas routing topology is more dynamic and takes into consideration the congestion at various nodes. In the following we study both of these problems (i.e., topology generation and routing) in more detail.

TOPOLOGY GENERATION

In the system under investigation, we assume that the topology of the BSs (designed by the service providers taking into account the mobile user distribution, topography, traffic patterns, etc.) is known. A number of FRNs will be placed according to some criteria such as covering a given geographical area with the fewest number of FRNs or such that the overall average path length in the system is small (i.e., each FRN can reach a BS with a small number of hops). These criteria might work against each other, and system parameters should be chosen by taking into account the trade-off between the average path length and the geographical area that needs to be covered.

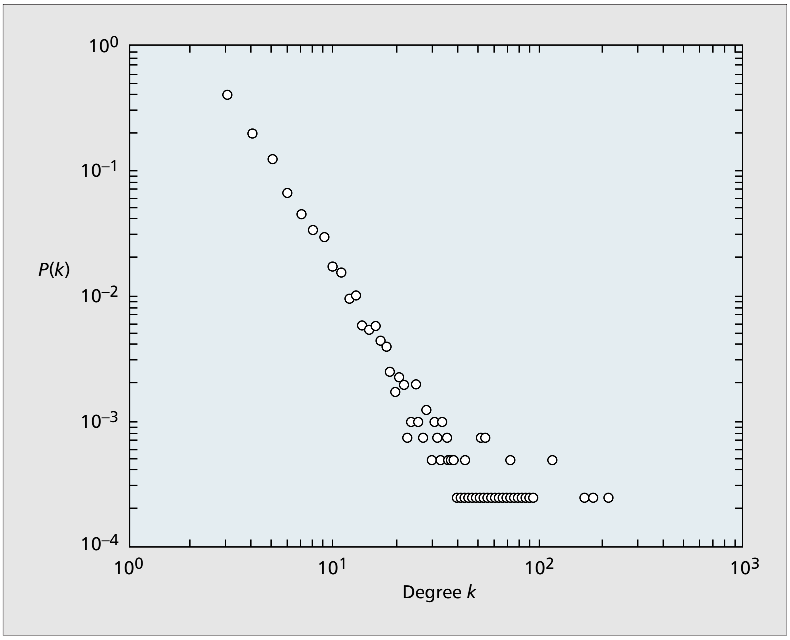

Figure 4. *Power-law degree distribution for the scale-free network with 4000 nodes.*

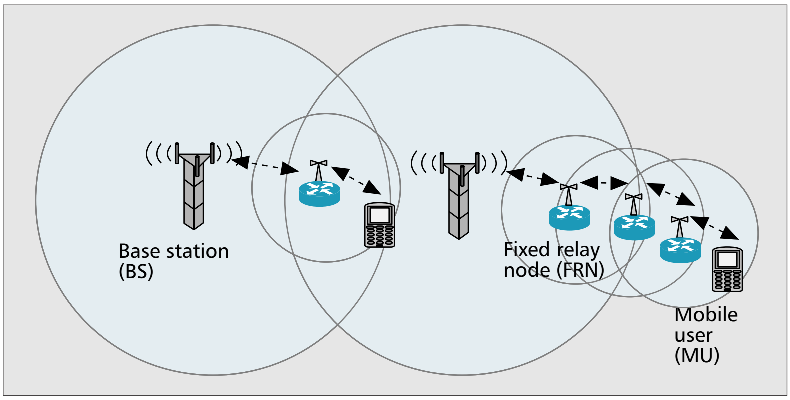

Figure 5. *An example of a wireless access network.*

While generating the topology of the overlay FRN network, we make use of the preferential attachment feature of the BA algorithm (illustrated in Fig. 3). In wired networks, attaching a new node to a highly connected node and hence developing topologies such that the degree distribution of the nodes shows the power-law characteristic is possible. However, this is not directly applicable to wireless networks, since being highly connected in the wireless case means the FRNs have many neighbors in their coverage area (i.e., the FRNs are clustered around a few FRNs). Therefore, in wireless networks the attachment of a new node (i.e., an FRN) to the other already existing connected nodes must also take into account the transmission range of the node and its reachability to neighboring nodes. Reachability is determined from the transmitted power of the node such that it does not increase

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Input: Range of FRNs (r), range of BSs (R), number of FRNs (n), length of the square shaped network (a),
coordinates of the BS centers ([x,y]), upper limit on the number of neighbors (K)
Output: Coordinates of the n FRNs ([xr,yr])

Generate random x and y coordinates for the 1st FRN
n_bs ← 0
Do

    (x0,y0) ← uniform random variables in the range [0,a]
    d ← distance from the BSs
    n_bs ← the number of BSs that are less or equal to R units away from the 1st FRN
While n_bs = 0

For i ← 2:n
    Generate random x and y coordinates for the i-th FRN
    (x0,y0) ← uniform random variables in the range [0,a]
    flag ← 0
    while flag = 0
        d ← distance from the BSs and the FRNs
        n_bs ← the number of BSs that are less than or equal to R units away from the new FRN
        n_frn ← the number of FRNs that are less than or equal to r units away from the new FRN
        if n_bs ≠ 0 or n_frn ≠ 0
            if n_frn ≤ K
                xr(i) ← x0
                yr(i) ← y0
                flag ← 1
            else
                (x0,y0) ← uniform random variables in the range [0,a]
            End
        End
    End
End
```

Figure 6. *The FRN placement algorithm.*

interference on neighboring nodes beyond a certain acceptable limit.

To avoid clustering of FRNs in certain geographical areas, we propose to attach new FRNs to the already placed FRNs that have at most K neighbors at the time of attachment instead of placing them near highly connected FRNs in the network. The limit K is a design parameter and determines the extent of coverage that can be achieved by a given number of FRNs, and the average path length that is achievable between the FRNs and BSs. The placement algorithm is shown in Fig. 6.

Clearly, the choice of K will have an impact on the average path length and hence scalability of the network. Assume that the total number of FRNs to be placed in the network is fixed. If K is chosen to be small, the geographical area that can be covered by the FRNs will be large. However, in this case the average path length (i.e., the average number of hops between an FRN and the nearest BS) will be high. On the other hand, if K is chosen to be large, the average path length can be reduced, resulting in a smaller area covered by the same number of FRNs. Therefore, there is a trade-off between the number of FRNs necessary to cover a certain area and the average path length. Moreover, when K is large, since the FRNs are most likely to be clustered around BSs, disjoint clusters of FRNs might be formed. This in turn will reduce the number of BSs an FRN can reach, and hence the likelihood of finding an alternative noncongested BS will be reduced as well.

In the following, we study the impact of K on the average path length and clustering coefficient of the generated network, where the number of BSs and FRNs is 3 and 100, respectively. Figure 7 shows the normalized average path length and clustering coefficients for different K values. Observe that when K is increased to 5, the average path length is reduced significantly, and a reasonable clustering coefficient (i.e., greater than 0.2) is achieved. (Note that, e.g., for the Internet the clustering coefficient is measured to be greater than 0.18, whereas for the Web it is measured to be 0.1078 [1].) After a point, allowing more neighbors does not affect the path length and the clustering coefficient. This suggests that to achieve small world effects in wireless networks, one does not need to choose a very high K value.

In summary, depending on the number of FRNs and the size of the geographical area that needs to be covered, the placement of the FRNs may become an important problem. From the service provider's point of view, it is desirable to cover a geographical area with as few FRNs as possible, reducing overlapping areas to a minimum. However, as seen in Fig. 7, by doing so the number of neighbors (from the range perspective) of each FRN is decreased, and hence the average path length (i.e., average number of hops) in the network is increased, making it harder to meet quality of service (QoS) requirements such as delay and bandwidth for both real-time and non-real-time traffic. By choosing an appropriate K value, small world effects and hence scalability can be achieved.

ROUTING OF TRAFFIC VIA FIXED RELAY NODES

Once the FRNs are placed in the geographical area, the next step is to route the traffic among the FRNs. The routing criteria can be minimizing number of hops, minimizing the number of congested links, maximizing network throughput, minimizing delay, and so on. In this sense, the location, selection, and number of FRNs become an important design parameter. In this work, the routing scheme will be designed to achieve high system utilization (efficient use of resources such as bandwidth). To this end, we design a load-balancing-based routing scheme. The objective is to pick the route with the fewest number of hops to the least loaded BS. Since the least loaded BS may not be the one that can be reached by the minimum number of hops, a joint performance metric needs to be formed.

First, let us assume there is no load balancing. When a mobile user (MU) wants to establish a new connection, it sends a request to a nearby node (FRN or BS) if it is covered by one. If a node is found, a possibly multihop route is formed to the terminating node (BS) via the FRNs in the geographical coverage area. The routing scheme employed is based on a shortest path algorithm and can be assumed to be one of the classical ad hoc routing algorithms such as Ad Hoc On-Demand Distance Vector routing (AODV) or Dynamic Source Routing (DSR). The downlink can use the reverse path or another route to the MU.

As expected, having a scale-free network will make QoS provisioning easier, since the average path length in the system will be small. Applying the BA algorithm to topology generation helps us achieve a scalable overlay network. However, depending on the locations of the FRNs, some FRNs and also BSs might need to serve an amount of traffic that is more than their capacity. Therefore, even though the placement of FRNs might guarantee a minimum number of hops to the BSs, it might not guarantee that the delay is at an acceptable level. Hence, we also need to design an effective routing scheme. To this end, we propose to use a load-balancing-based routing algorithm, which aims to balance the load among both BSs and FRNs. We are currently investigating whether "scale-free" concepts can be applied to our routing algorithm as well. We conjecture that the BA algorithm can be applied by routing the traffic through a given number of high-capacity hub FRNs, thus decreasing the complexity of the routing algorithm and easing traffic management among the overlay relay network.

Method 1: Load Balancing among Only BSs — In this approach, when an MU wants to make a connection, if it is covered by a BS, it gets attached to it if the BS is not congested. If the BS covering the MU is congested, either the MU is put in a queue or an alternative route to another BS is found through the FRNs. If the MU is not covered by any BSs, but is covered by FRNs, a route to a BS is formed via the FRNs. The choice of the BS to which to be attached depends only on the load at the BSs (i.e., the load of the intermediate FRNs is not taken into account). Therefore, all packets belonging to an MU follow the same route to a given destination BS.

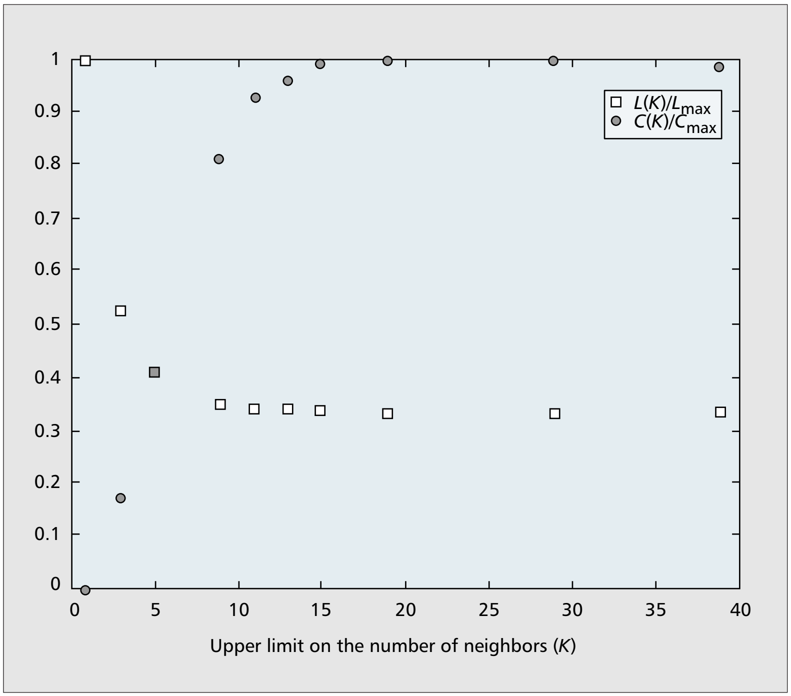

Figure 7. *Normalized average path length [$L(K)/L_{max}$] and clustering coefficient [$C(K)/C_{max}$] vs. limit on the number of neighbors.*

Method 2: Load Balancing among FRNs and BSs with No Change in Destination BS — In this approach we take into account the load of both BSs and FRNs. When an MU requests service, it connects to a BS directly or via FRNs depending on its location. In this approach the destination BS is decided while initiating the connection and does not change throughout the connection. However, depending on the load of the intermediate FRNs, the route on which an MU sends each packet can be different. Once a packet reaches an FRN, the next hop is decided by taking into account the load of the neighboring FRNs and the number of hops between the neighboring FRNs and the destination BS. The load is defined as the number of packets in the queue of a node (BS or FRN).

Method 3: Load Balancing among BSs and FRNs with Change in Destination BS — In this approach we again take into account the load of both BSs and FRNs. In this approach, although the least loaded BS is chosen to be the destination while initiating the connection, it can be changed during the connection. Once a packet reaches an FRN, the next hop is decided by taking into account the load of the neighboring FRNs and the number of hops between the neighboring FRNs and *all* of the BSs in the geographical area. In this case we take into account all BSs, since the distance between the least loaded neighboring FRN and the initially chosen BS might be too high.

We studied the performance of these three load balancing methods and compared the performance of these schemes with a shortest path

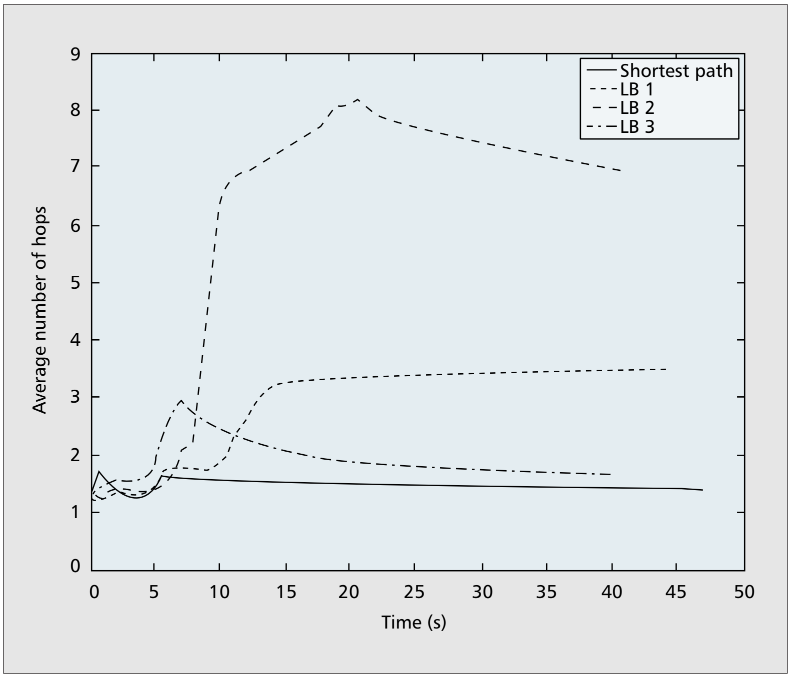

Figure 8. *Average number of hops traveled per packet between MUs and BSs over an observation interval.*

algorithm. The number of BSs and FRNs in the network is assumed to be 3 and 50, respectively. The transmission rate of the BSs and FRNs is assumed to be 100 Mb/s and 10 Mb/s, respectively. While choosing the BS to which the traffic will be routed, we take the queue size in the BSs into account. When load balancing is employed, first the load of the closest BS is checked. If the load of this BS is higher than 90 percent of the capacity of the BS, an alternative BS with less load is chosen. If such a BS cannot be found (i.e., all BSs are congested or there is no alternative route), the packets are forwarded to the closest BS. We assume that the MUs generate traffic according to a Poisson process, and message lengths are exponentially distributed. The locations of the MUs are generated according to a uniform distribution. The network topology is generated using the algorithm presented in the previous section, where $K = 1$.

Figure 8 shows the average number of hops traveled per packet between MUs and BSs over an observation interval for different routing algorithms. As expected, the average number of hops is smallest when a shortest path algorithm is used. Although both load balancing methods 2 and 3 take into account the load of the FRNs on the route from the MUs to the BSs, their performance differs significantly. For example, for an observation duration of 20 s, the packets travel on average eight and two hops if load balancing methods 2 and 3 are used, respectively. This is due to the fact that when load balancing method 2 is used, the destination BS is not changed for the whole connection; that is, the alternative routes the packets take on might be very long, increasing the average number of hops per packet. On the other hand, since the loads of and distances to all BSs are taken into account when a route is selected with load balancing method 3, the average number of hops per packet is comparable to that of the shortest path algorithm.

CONCLUDING REMARKS AND FUTURE WORK

In this article we have articulated on the potential application of small world and scale-free network concepts to wireless networks. We have particularly focused on achieving scalability in a joint cellular and fixed relay node network. We have divided the problem into topology generation and routing. We have shown that using the proposed modified BA algorithm, a network topology that exhibits small world properties can be generated. Hence, the placement of the fixed relay nodes plays an important role in achieving scalability in the network. We have also provided a methodology for routing where the objective is to achieve a load balanced network so that the available resources are used efficiently and the cellular network is more robust to base station failures (both of these are self-organizing features in a wireless network). While using the FRNs to provide alternative routes to the BSs, we also consider the number of hops on each route so that the delay experienced by mobile users is at acceptable levels.

Existing complex networks, such as the internet and airline networks, have been observed by several researchers to be self-organizing and scale-free regardless of the number of nodes in these networks. With the increased demand in mobile applications, it is anticipated that wireless nodes will proliferate, and wireless networks with large numbers of nodes will be formed. Providing QoS, reliability, and traffic management in such networks is thus desirable. Many studies focus on these issues, assuming such networks exist and have a certain topology. In our work we tackle a different problem, and try to engineer legacy cellular wireless networks such that they are self-organizing. Although our preliminary results seem promising, it is not yet clear under which conditions scale-free wireless networks can indeed be achieved. In particular, we are currently investigating the relation between the number of fixed relay nodes, connectivity degree, and the area that needs to be covered. Intuitively, a high limit on the number of neighbors is desirable for a smaller number of hops between nodes, for alternative routes, and for scalability. However, having a high number of neighbors might introduce vulnerability to the network; for example, if a highly connected node that relays the traffic of many other nodes goes down, the service of several nodes might be disrupted. We are currently in the process of determining the optimum number of neighbors to achieve scalability, small average path lengths, high coverage, and low vulnerability to failures. We would like to determine if and to what extent these properties can be achieved, and provide guidelines for the design of such networks for different network sizes.

Another important point that needs to be further investigated is the implications of having a scale-free wireless network on having self-organizing capability. Although it has been reported that several self-organized networks (e.g., the Internet and airline networks) exhibit scale-free properties, it is not yet clear if having the scale-free characteristic in and of itself is sufficient to achieve self-organization.

Finally, although we anticipate that the approach can be extended to other wireless networks with or without centralized controllers as well (e.g., wireless ad hoc and sensor networks with large numbers of nodes [10]), further research is needed to determine whether small world and scale-free effects can be created in such networks.

Existing complex networks, such as the Internet and airline networks, have been observed by several researchers to be self-organizing and scale-free. In our work, we tackle a different problem and try to engineer legacy cellular networks such that they are self-organizing.

ACKNOWLEDGMENTS

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BIOGRAPHIES

Sudhir Dixit [SM'95] is currently a Nokia Research Fellow and works on next generation wireless networks. From 1996 to October 2003 he was a senior research manager, focusing on IP/ATM, wireless, content networks, and optical networks. Prior to that he worked at NYNEX Science & Technology (now Verizon), GTE (now Verizon), Codex Motorola, Wang, Harris, and STL (now Nortel Europe Labs). He has published or presented over 150 papers, published three books, and holds 11 patents. He received a B.E. degree from MANIT, Bhopal, India, an M.E. degree from BITS, Pilani, India, a Ph.D. degree from the University of Strathclyde, Glasgow, Scotland, and an M.B.A. degree from Florida Institute of Technology, Melbourne. He represents Nokia on the Steering Board of the Wireless World Research Forum, and is also Vice Chair of the SIG on Self-Organization of Wireless World Systems.

Evşen Yanmaz [S'01] received a B.S. degree in electrical and electronics engineering from Bog–aziçi University, Istanbul, Turkey, in 2000, and an M.S. degree in electrical engineering from State University of New York (SUNY) at Buffalo in 2002. Currently, she is working toward a Ph. D. degree in electrical and computer engineering at Carnegie Mellon University, Pittsburgh, Pennsylvania, on congestion in cellular communication systems and dynamic load balancing schemes. Her other interests are in self-organizing networks and QoS provisioning in next-generation wireless communication systems.

Ozan K. Tonguz [S'86, M'90] received a B.Sc. degree from the University of Essex, England, and M.Sc. and Ph.D. degrees from Rutgers University, New Brunswick, New Jersey, all in electrical engineering. He is currently a tenured full professor in the Department of Electrical and Computer Engineering at Carnegie Mellon University (CMU). From 1990 until joining CMU in August 2000, he was with the Electrical and Computer Engineering Dept. of SUNY Buffalo, where he was promoted to full professor in 1998. From 1988 to 1990 he was with Bell Communications Research (Bellcore) doing research in optical networks and communication systems. His current research interests are in wireless networks and communication systems, optical communications, high-speed networking, and satellite communications. He has authored or coauthored more than 150 technical papers and a book chapter He is also a Co-Director (Thrust Leader) of the Center for Wireless and Broadband Networking Research at CMU. His homepage can be found at http://www.ece.cmu.edu/~tonguz