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A model for self-organizing large scale wireless networks

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Introduction

Recent developments in the design of wireless mobile telecommunication systems have adopted the concept of ad-hoc networking and routing, where each mobile node assumes a *double* role of terminal and router [1]. This novel feature provides a remarkable increase in the level of autonomy with respect to the fixed communication infrastructure and opens the door for new forms of self-organization in the network. Ad-hoc networking is currently being considered for relatively small-scale systems such as batlefields, interactive lecturing, and local emergencies. Moving network functionalities into the mobile node, however, is extremely appealing for large-scale wireless systems as well, for fundamental reasons ranging from power consumption, to robustness, to infrastructure costs [2].

The complex flexibility of a large-scale distributed network must be matched by a corresponding flexibility in the management of resources. This feature in turn requires the adoption of a physical-layer transmission technique providing large amounts of resources defined by multiple parameters. Ultra Wide Band (UWB) radio techniques, in particular, are ideally suited for this purpose, given the intrinsic flexibility of their transmission parameters (Time-Hopping codes, pulse duration and shape, power levels, etc). An Open Mobile Access Network (OMAN) following the above guidelines has recently been proposed [3].

When terminals are capable of addressing and routing, they can serve as repeaters in a given communication link. Information then travels along paths made of multi-hop connections, similar to radio bridges in the old days (Fig. 1). In current ad-hoc networks, multi-hops are used to reach terminals that are located beyond physical reach. In contrast, multi-hop connections here are viewed from a different perspective. To set up a connection, a terminal does not necessarily establishes a direct physical link, even when the power of its transmitter is sufficient to achieve a one-hop path. Rather, it might select a multi-hop path for the connection, in order to reduce emitted power. As a beneficial side effect, interference noise is reduced as well. The drawback is that signalling overhead increases with the number of hops in the path.

The fundamental problem then is the selection of relevant parameters and the construction of an associated cost function to compare and select paths, and solve the routing problem. The cost function should incorporate power constraints, as well as other factors, such as signalling overhead. The strategy should also take into account the possibility of using existing active links between nodes, as possible intermediate hops, whenever setting up a new connection.

The cost function of a network of users, together with their connectivity requests, determines the topology of the network of active links at a given time and its temporal evolution. This topology could end up for example in a fully connected graph, with all nodes connected directly to each other, or in a graph in which nodes are connected directly only to their closest neighbours, or in an intermediate case. Analysis of the resulting class of topologies can be used to assess the quality of the cost function and guide its design.

In this paper, we propose a model for a distributed wireless system and construct a realistic set of parameters and associated class of cost functions. We provide results obtained by simulation that corroborate the above metodologies, and provide directions for future research.

Model and routing

Model

The model we propose consists of:

- $S = \{i\}$: a set of terminals;
- $D = (d_{ij})$: the matrix of pairwise distances between the elements of S ;
- $r_{ij}(t)$: maximum rate (capacity) on the direct link between i and j at time t;
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- $a_{ij}(t) = \begin{cases} 0 & \text{if direct link between } i \text{ and } j, \text{or } j \text{ and } i, \text{is being used at time } t \\ 1 & \text{if both are not used} \end{cases}$
- $R_{ij}(t)$: requested rate of transmission between i and j at time t
- $c_{ij}(t)$: cost of transmission from i to j at a given rate $R_{ij}(t)$, defined as:

$$c_{ij}(t) = \begin{cases} \infty & \text{if } R_{ij}(t) > r_{ij}(t) \\ C_0 a_{ij}(t) + C_1 R_{ij}(t) d_{ij}^{\alpha} & \text{if } R_{ij}(t) \le r_{ij}(t) \end{cases}$$

A description of the model is shown in Fig.2.

In this first model description, we suppose a universe with a fixed set of terminals at fixed locations. Mobility and related mechanisms of entry and exit from the universe will be introduced at a later stage of modeling. Within the universe, each terminal is within reach of any other terminal. Thus, the universe can be understood as a coverage area. Each link is characterized by the maximum achievable rate at time t defined as the capacity of the link $r_{ij}(t)$.

The cost function is infinite when the desired rate of transmission is above the capacity of a given link. When it is less than the capacity, then we model the cost fucntion as the sum of two terms: a fixed cost for setting-up a new connection ($C_0 a_{ij}(t)$), related to signalling costs, and a term reflecting power costs proportional to d_{ij}^{α} and the requested rate of transmission $R_{ij}(t)$. Note that defining $R_{ij}(t)$ implies that we consider classes of traffic with guaranteed quality of service (QoS). Best effort classes of traffic are not considered in the model at the present stage.

We discretize time with a time scale ΔT such that there is at most one new request per interval ΔT in time ΔT , and ΔT is large with respect to the switching time scale of the of the terminals.

Routing algorithm

Assume that terminal i wants to send data at rate $R_{ij}(t)$ to terminal j at time t. The routing algorithm proceeds as follows:

1. compute the cost of all links using the previous definition of the cost function;
2. find the path of lowest cost using the Viterbi algorithm or dynamic programming;
3. update all the capacities along the selected path by reducing each one of them by $R_{ij}(t)$. In addition, update all $a_{kl}(t)$ along the path accordingly;
4. wait for the next call and go back to 1.

This approach to routing requires each terminal to have a global view of the network. This view could be achieved through a dedicated channel, or through low-cost repeated propagation of location and activity messages by each terminal. Alternatively, optimal routing could be approximated with sub-optional paths obtained by local propagation algorithms.

Simulation

In preliminary simulations, the universe S includes 25 nodes. These nodes are located at the vertices of a regular lattice (Fig.3). The universe is the intersection of the set of reachable nodes by each node (Fig.4). Therefore, within S, each node can reach any other node with only one hop i.e. a direct link. In the present analysis, the terminals are non-mobile within S.

For each node and each link, parameters of the model are set, and the cost function is computed as indicated in the previous paragraph. If during connection establishment two routes with same cost function value but different number of hops are found, then the route with lower number of hops is selected.

Note that due to the way the cost function is defined, multi-hops are favored during initial stages. In fact, when no link is active, a multi-hop route is selected over a direct link since it leads to lower power consumption. However, as new connections are formed, some of the nodes saturate in terms of capacity. Moreover, active links are favored because they lead to lower signalling cost. New connections thus start using shortcuts to reach destination nodes whenever directionally favorable pre-established active links are present. We estimated the probability that the routing path associated with a new connection request contains an active hop. This parameter may help understanding which type of network topology is generated after a number of connections are formed. Results show that the probability of using an existing hop rapidly tends to a high value (about 0.85), suggesting a small-world topology [4,5]. Small-world networks are characterized by having a small average path length between nodes vs. a high degree of local clustering coefficient. This emerging small-world topology is a positive feature since both power consumption (high-density of local connections) and signalling overhead are reduced.

Conclusion

We have introduced a new model for large scale distributed wireless networks. Under a small set of realistic assumptions, we have shown that activity in this network rapidly releases to a so-called “small world” topology [4,5]. Such topology is characterized by sparseness and the fact that two nodes can be connected through a small number of hops. It is perhaps reassuring to note that the emergence of small world phenomena has been recognized in a variety of complex distributed systems ranging from metabolic networks to social organizations [6].

Directions of research which are currently being investigated include introduction of terminal mobility and interactions between different coverage areas, variations in the cost function, and definition of classes of nodes with different capabilities, distinguishing for instance plain terminals from radio access nodes to the fixed network infrastructure.

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References

[1] C.R.Lin and M.Gerla “Adaptive clustering for mobile wireless networks, ” IEEE Journal on Selected Areas in Communications, vol.15, no.7, Sept.1997, pp 1265-1275.

[2] J. P. Hubaux, Th. Gross, J. Y. Le Boudec, M. Vetterli "Towards self-organized mobile ad hoc networks: the Terminodes project," IEEE Communications Magazine, January 2001, http://www.terminodes.org/publications.html.

[3] H.Luediger, S.Zeisberg, M.G.DiBenedetto, N.Blefari-Melazzi “Outline of an Open Mobile Radio Access Network,” Proceedings of the European Wireless 2000, Dresden (D), September 12-14, 2000, pp.77-83.

[4] D.J.Watts and S.H.Strogatz “Collective dynamics of ‘small-world’ networks,” Nature, vol.393, June 1998, pp.440-442.

[5] H.Herzel “How to quantify ‘small-world networks’?,” Fractals, vol.6, no.4, 1998, pp.301-303.

[6] L.A.Nunes Amaral, A.Scala, M.Barthélémy, H.E.Stanley “Classes of small-world networks,” Proc. Nat. Acad. Sci. USA, Vol 97, Issue 21, Pages 11149 - 11152 (2000).

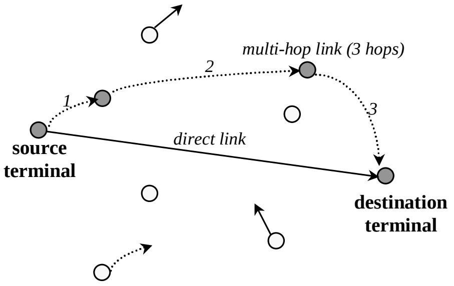

Figure 1 – Example of a connection between a source terminal and a destination terminal through a direct path (black line) i.e. a one hop link, and a multi-hop link (dotted line) made of 3 hops.

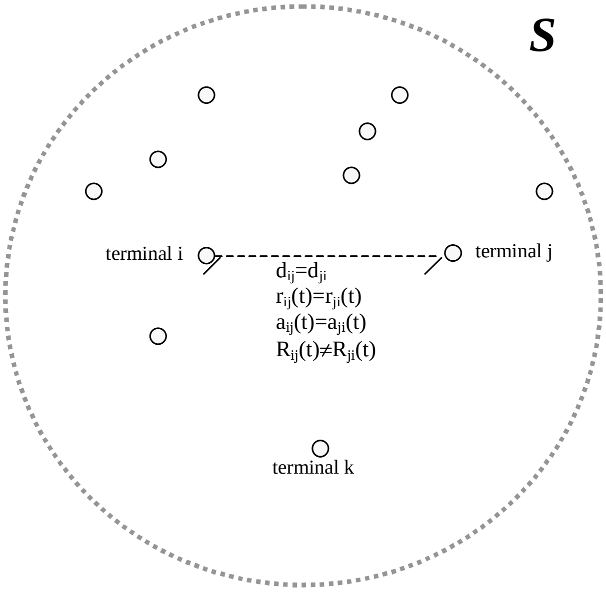

Figure 2 – Model

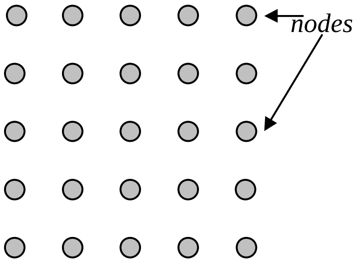

Figure 3 – Location of the nodes in the simulator.

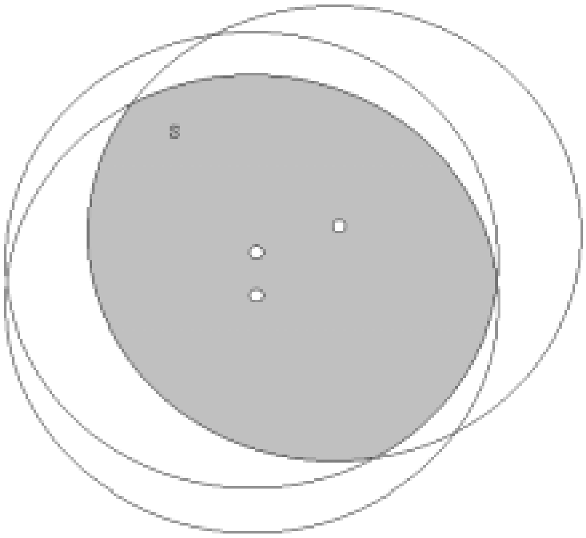

Figure 4 – Representation of the Universe S in the simulator. Within S each node is physically reachable from any other node.