Buletinul Ştiinţific al Universităţii "Politehnica" din Timişoara

Seria ELECTRONICĂ şi TELECOMUNICAŢII
TRANSACTIONS on ELECTRONICS and COMMUNICATIONS

Tom 51(65), Fascicola 2, 2006

How to Choose a Model for Ad hoc Wireless Networks

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Abstract – This paper studies ad hoc wireless networks using a network information theory point of view. Two classes of networks are analyzed in the paper, considering the location of the nodes and the traffic graphs: arbitrary and random. Three theoretical models are presented for multi-hop transport, and each of them takes into account different aspects of these types of networks: protocol restrictions, interference, bandwidth. The minimal model parameters are inventoried, and their influence on the model behavior is discussed. New metrics are introduced, to allow a more accurate representation of the information flow in wireless networks. The current status and difficulties of the traditional information theory to describe this multiple input-output system are discussed. The third model that we introduce is an extension of the interference model, that adds a new parameter, bandwidth, and an optimum criteria using results from information theory of MIMO systems. The intention to bring together information theory and network protocols is the right way to analyze the limitations of the current implementations of such systems.

Keywords: wireless networks, ad hoc networks, network information theory, network transport capacity, network model metrics.

I. INTRODUCTION

Wireless networks are communication networks that use radio as their carrier. A wireless ad hoc network is a decentralized network of nodes with radios, possibly mobile, sharing a wireless channel and asynchronously sending packets to each other, generally over multiple hops. The most notable characteristics of an ad hoc network are a lack of infrastructure, multi-hop communication by cooperative forwarding of packets, distributed coordination among nodes, dynamic topology, and the use of a shared wireless channel.

The potential for deployment of ad hoc networks exists in many scenarios, for example, in situations where infrastructure is infeasible or undesirable, like disaster relief, sensor networks, etc. Ad hoc networks also have the potential of realizing a free, omnipresent communication network for the community. This comes with a price, too. Due to the lack of a central unit, routing, medium access and power control rise many problems that did not exist in wired or cellular networks.

Medium access in ad hoc networks is a complex problem. Multiple access schemes popular in cellular networks are not easy to implement in ad hoc networks because of the need to dynamically allocate resources efficiently.

Another aspect of the wireless networks is reducing the interference caused by various transmissions, which is critical for the efficiency and scalability of any wireless system. This motivates transmission power control, which is a very complex problem for ad hoc networks.

In this paper we analyze some ad hoc networks wireless models, considering two possible scenarios: arbitrary and random network classes. Then, we discuss the metrics and parameters that can be used to characterize these communication systems in a network information theory fashion..

II. MODELS FOR ARBITRARY NETWORKS

We call *arbitrary* the class of networks that have arbitrary locations of the nodes, and arbitrary traffic patterns The wireless network model presented here consists of *n* nodes located arbitrarily in a limited area, a plane disc of unit area. Each node can transmit over the wireless channel with a maximum rate of *W* bps. However, each node can choose an arbitrary lower rate for the next transmission. The information is sent from node to node (multi-hop) to the final (arbitrary) destination.

As shown in Figure 1, several nodes can make successful transmissions simultaneously due to spatial separation and the absence of interference from others. A successful transmission over one hop is conditioned by the access to the medium and the level of interference with the neighboring nodes. For medium access, a *protocol model*, and for power related issues, a *physical model* from [1] will be presented. For both models, the nodes are denoted X_i, which also stands for the location of the node.

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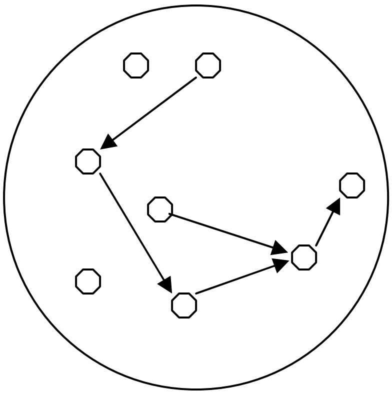

Figure 1. Multi-hop transmission in an ad hoc wireless network

The Protocol Model takes into account the distance D_{ij} between transmission nodes compared to the distance D_{kj} between interference nodes and the destination node. The transmission is considered successful if:

$$\begin{aligned} &D_{kj} \geq (1+\Delta) D_{ij}, \\ &D_{kj} = \left|X_k - X_j\right|, \qquad D_{ij} = \left|X_i - X_j\right| \end{aligned} \tag{1}$$

The node X_i transmits on one channel to node X_j, and X_k is another node transmitting simultaneously on the same channel. The parameter Δ stands for the guard zone specified by the protocol to prevent neighboring nodes from using the same channel at the same time.

The *Physical Model* takes into account the power transmission level chosen by each node that is simultaneously transmitting at some instant over a certain channel. Let $\{X_k; k \in T\}$ be the subset of nodes that transmit at the same time and P_k the power level chosen by node X_k. The transmission from node $X_i, i \in T$ is successfully received by a node X_j if the *signal-to-interference and noise ratio* (SINR) is larger than a threshold β:

$$SINR = \frac{\dfrac{P_i}{\left|X_i - X_j\right|^{\alpha}}}{N + \sum\limits_{\substack{k \in T \\ k \neq i}} \dfrac{P_k}{\left|X_k - X_j\right|^{\alpha}}} \geq \beta \tag{2}$$

In equation 2, *N* denotes the power level of ambient noise, and α is the attenuation exponent, as the signal power decays with distance as $r^{-\alpha}$. We could suppose $\alpha > 2$, which is true for a limited neighborhood around the transmitter.

III. MODELS FOR RANDOM NETWORKS

The *random* networks class model presented here consists of *n* nodes located randomly, independently and uniformly distributed, in a limited area, a plane disc of unit area. Each node will transmit to a randomly chosen destination with a maximum rate of *W* bps. However, each node will choose a random rate for the next transmission. The information is sent by multi-hopping to the final destination. The destination node is independently chosen as the node nearest to a randomly located point (uniformly and independently distributed), thus destinations are at the average distance of 1 m.

As a opposed to the arbitrary networks, we assume that all transmissions employ the same nominal power. The two models, protocol and physical, are analyzed here.

In the *Protocol Model*, all transmissions share a common range denoted *r.* The distances D_{ij} (between transmission nodes) and D_{kj} (between interference nodes and the destination node) are compared now against this common range. The transmission is considered successful if these two conditions are met (see notations in eq. 1):

i) the transmission distance is less than *r*:

$$D_{ij} \leq r \tag{3}$$

ii) other nodes that transmit on the same channel are outside the transmission region given by *r* and the guard zone Δ:

$$D_{kj} \geq (1+\Delta) r \tag{4}$$

The *Physical Model* assumes that all nodes use the same power level *P* for all the transmissions. As in arbitrary networks case, $\{X_k; k \in T\}$ is the subset of nodes that transmit at the same time. The transmission from node $X_i, i \in T$ is successfully received by a node X_j if the SINR is larger than a threshold β:

$$SINR = \frac{\dfrac{P}{\left|X_i - X_j\right|^{\alpha}}}{N + \sum\limits_{\substack{k \in T \\ k \neq i}} \dfrac{P}{\left|X_k - X_j\right|^{\alpha}}} \geq \beta \tag{5}$$

IV. METRICS AND ANALYSIS

The constraints defined by the Protocol Model are local. They only require certain regions of transmitters to be free of receivers. On the other hand, the Physical Model considers the cumulative interference due to all the nodes in the network. Thus, intuitively it appears that the Physical Model is a much more restrictive model, and would offer lower capacity. However, going deeper into analyzing both model's capacity may lead to invalidating this intuition. The purpose of the theoretical model of a communication system (and not exclusively communication) is to provide a means for deriving certain bounds on the performance parameters that are of interest.

One such parameter is the *network transport capacity* (NTC), i.e. how much information can possibly be transported, which can be representative for a class of wireless networks, by providing the limitations and the scaling capacity of different network architectures and protocols. The unit chosen by [1] for measuring the NTC is taking into consideration the amount of information that is transmitted successfully over time and space: the *bit-meter.* This metric, derived from information theory, is the quantity of network transported information when one bit has been transported a distance of one meter towards its destination. The same bit is taken into account only once in the case of one source transmitting to multiple destinations.

This metric combined with the individual transmission rates for each node offers an appropriate measure unit for the NTC, the *bit-meter per second* (bmps). If compared to Shannon's information capacity theorem, the bit-meter is analog to the bit-per-channel-use that measures channel capacity, and the bit-meter per second is analog to the bit-per-second measuring data rate that can be achieved using the channel.

V. THE INFORMATION THEORY MODEL

Information theory provides models and bounds that describe communications systems, and assume an information source, a transmission channel and a receiver. In the recent years, efforts are taken to use these elements to derive theoretical bounds for systems with many senders and receivers. The new flavor is called Network Information Theory and was first studied in [2]. The notions defined for single channel can be used to derive models for multiple user communications, but seem not sufficient to include all the effects that may appear: interference between users, distributed communication, bursty sources, simultaneous access, etc.

Network channels can be divided into three categories:

- MIMO (Multiple sources, multiple receivers) – this is the most general network case, where many users share the same medium to communicate, and is still one of the unknowns with respect to the model to be used.

- SIMO (Single source, multiple receivers) – also known as the broadcast channel.

- MISO (Multiple sources, single receiver) – also known as the multiple access channel.

A pure Shannon approach is not sufficient to derive bounds on channel capacity for networks. Information theory deals only with noise affecting the transmission, but cannot provide a model for packet arrival with delay. Network theory, on the other hand, is more empirical, and was based on continuous tweaking through performance observation. The matter of noise and interference is viewed as simple as "bad packet rate".

The triumphs of network information theory, as presented in [2] are mainly in the SIMO and MISO channels area. For these two cases, the channel capacity theory has taken the form of achievable rate regions that allow the users to transmit at maximum rates with a low probability of error.

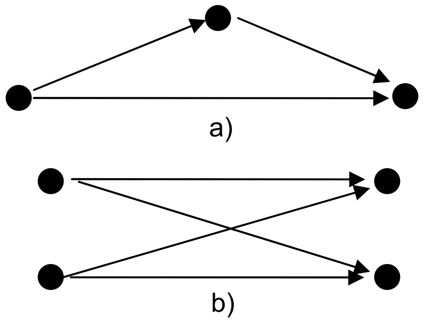

Figure 2. Examples of MIMO simple channels: a) the relay channel, b) the interference channel

The cases of the relay and interference channels are still in need of a general purpose information theory. The difficulty comes from the big number of ways of interaction between peers. In relay mode, nodes can act as repetitive units, amplifiers or coherent repetitive units. In the case of interference channel, some of the nodes can cooperate in canceling the interference introduced by other nodes.

The two network models presented in [1], do not take into account limited bandwidth and rate restriction for a successful transmission. The latter may be seen as embedded into eq. (2) and (5), i.e. the nodes transmit at different rates, and due to SINR, some transmissions may not be successful. We propose another approach to multi-node transmission, taking into account bandwidth, power, channel capacity and thus the achievable rate.

Channel capacity for a multi-access channel was studied in [2], and the results are used to describe transmission between nodes. According to this, transmission is successful (at one node), if the sum of all the incoming transmissions rates W_i does not exceed channel capacity C to that node, see eq. (6).

$$\sum_{i=1}^{n} W_i \le \frac{1}{2}\log(1+\sum_{i=1}^{n} SNR_i) = C_{node} \quad (6)$$

Having several transmissions, at the same time, towards a node, the only combination of rates that yields safe decoding of the output is the achievable rate region ($W_1,\ldots W_n$). The decoding is performed first on the lowest rate data, then this is subtracted from the mixed signal and next lowest rate is used for the new signal, and so on, until the highest rate data is decoded.

Considering a limited bandwidth transmission, and using the Physical model results, we consider the capacity of the channel between two nodes X_i and X_j (the transmission bandwidth is B_{ij}):

$$\begin{aligned} C_{ij} &= B_{ij}\log_2(1+SINR) \\ &= B_{ij}\log_2\left(1+\frac{\dfrac{P_i}{\left|X_i - X_j\right|^{\alpha}}}{N_0 B_{ij} + \sum\limits_{\substack{k\in T\\ k\neq i}} \dfrac{P_k}{\left|X_k - X_j\right|^{\alpha}}}\right) \end{aligned} \quad (7)$$

The result in (7) seems more restrictive than (6), as it forces an upper bound on the rate that can be used between the two nodes, so that transmission is performed successfully. In fact these two results have distinct roles in helping the design of an optimal rate scheme:

- the sum of all rates that are used at the same time towards one node should not exceed the capacity defined in (6), or, in other words, only a set of achievable rate transmissions will be decoded by the node;
- the rate of one particular transmission between two nodes should not exceed the capacity defined in (7); higher rates will not be decoded correctly.

Another remark is that the result can be used to calculate the overall NTC of a specific network class. Further study will provide what is the best combination of capacities as in (6) and (7) that will maximize the NTC.

This model offers at least one more parameter that will be taken into account when deriving the upper bound of NTC: bandwidth. As more parameters can be included in the model, the more restrictive it becomes, but it comes closer to the real world. Bounds are useful for developing of scheduling algorithms, assuming that are known the locations of all nodes and the overall traffic demand. These algorithms coordinate all transmissions temporally and spatially in a way to minimize collisions. If the model shows that the NTC decreases with *n* (as in the case of ALOHA system), this will help the designers to target their efforts towards developing smaller wireless networks, and inter-connecting them using wired transport.

VI. CONCLUSIONS

The paper introduces two types of models for the multi-hop ad hoc wireless network. First type consists of the Protocol Model that allows to identify successful transmissions based on the distance between nodes, and the Physical Model that is based on the signal-to-interference-and-noise ratio that affects the transmission from one node to another. To make things more generally, two classes of networks were used: arbitrary networks and random networks. The choice of having more than one class and more than one model is intended. The second type of models that we introduced, extends the existing modules by including more parameters (e.g. bandwidth). It uses an optimum criteria, the achievable rate problem, to relate NTC to rate and bandwidth. Having a simple feedback between nodes, because there is no controlling unit in ad-hoc networks, the maximum network throughput can be achieved by wisely choosing the rates, power and bandwidth. The network transport capacity, calculated for each model, will be able to drive the network designers in the right direction, when it comes to the choice of network parameters.

Together with a series of parameters that help to describe the behavior and performance of these networks, these models are a step forward towards creating theoretical models of communication that can allow us to study their limitations and seek opportunities for improvement. Distance was incorporated into these models, as new metrics were defined to allow the information theoretic approach (e.g. bit-meters per second).

There are still effects that are not introduced yet in the models. The channels employed do not take into account fading, multi-path propagation and other effects. However, the simplicity of these models allows for an initial determination of the capacity of the networks, and then, they can be developed in better models.

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