Performance of Symmetric Neighbor Discovery in Bluetooth Ad Hoc Networks

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Abstract: Ad hoc networking with Bluetooth requires an efficient way of discovering neighbor devices. Based on real-world measurements and simulations we are deriving optimal parameters for symmetric ad hoc neighbor discovery using standard Bluetooth procedures.

1 Introduction

Bluetooth is one of the candidate technologies for the implementation of wireless mobile ad hoc networks (MANETs). The first step of building ad hoc networks with any technology of course is neighbor discovery. Unlike the popular WLAN technology ad hoc neighbor discovery with Bluetooth is a non-trivial task due to the frequency hopping MAC scheme of Bluetooth.

This paper presents simulation and measurement results that show how to optimally use the standard neighbor discovery procedures of Bluetooth in order to perform ad hoc symmetric neighbor discovery. The experiments were performed with recent Bluetooth hardware conforming to Bluetooth version 1.1 (cf. [Blu01]).

Previous work on Bluetooth network formation (e.g. [ZBC01], [WTH02], [TMGB02]) concentrates on the network formation protocol and the resulting topology but does not discuss the underlying neighbor discovery method. To our best knowledge this is the first work that optimizes Bluetooth neighbor discovery using real-world devices.

2 Bluetooth Neighbor Discovery Procedures

The frequency hopping MAC makes neighbor discovery with Bluetooth significantly more complex than with single-channel technologies such as WLAN. As every device hops independently through the frequency space, a device that wants to discover its neighbors does not know which frequency to send on. Therefore, the Bluetooth specification ([Blu01]) defines the so-called inquiry procedure which helps to overcome this frequency uncertainty.

2.1 Standard Neighbor Discovery

The inquiry procedure defined for Bluetooth is an asymmetric process: A device that wants to be discoverable enters the *inquiry scan* mode whereas the other device enters the *inquiry* mode in order to discover its neighbors. Inquiry is conducted on 32 of the 79 Bluetooth frequencies. Devices in inquiry scan mode listen on a fixed frequency which is changed every 1.28 s.

As the discovering device does not know which frequency its neighbors are currently on, it repeatedly cycles through 16 frequencies $f_i \in [f_{center} - 7, f_{center} + 8]$ around a certain center frequency f_{center}. This set of frequencies is called a *train*. If the device to be discovered happens to listen on one of the 16 frequencies of train A then it may receive so-called ID packets from the discovering device. Depending on the clock offset between the two devices it may be necessary for the discovering device to switch from train A to train B which includes the other 16 frequencies. The discovering device switches trains every 2.56 s.

The overall duration of the inquiry procedure consists of two major components: a frequency synchronization delay and a random backoff. If both devices are on the same train, it will last at most 16 slots (10 ms) until the discovering device hits the correct frequency. Otherwise, up to 2.56 s have to pass in order for the discovering device to switch to the correct train B. Before sending an inquiry response, the scanning device enters a random backoff period, which may last up to 640 ms.

2.2 Symmetric Neighbor Discovery

Classical Bluetooth applications assume predefined roles for individual devices which at the same time leads to predefined neighbor discovery roles. For example, in an access point scenario it is usually the mobile device that tries to discover access points by using the inquiry procedure while access points make themselves discoverable by periodically turning on inquiry scan mode. In contrast to this, in ad hoc networking situations usually all devices are assumed to be equal. This demands for a symmetric method of neighbor discovery. Note that it is not sufficient to simply turn on inquiry periodically since intervals between two devices might align so badly that discovery between devices may take arbitrarily long or fail altogether (cf. [SBTL01]).

Salonidis et al. (cf. [SBTL01]) present and analyze a symmetric method for neighbor discovery where each device consecutively switches between the inquiry and inquiry scan mode. The residence time in each mode is a random variable that has been assumed to be either uniform or exponential. Salonidis et al. analytically derived that an expected neighbor discovery time of about 1 s would be feasible if the mean residence time was set to 600 ms.

However, these findings could not be verified in practice using current devices conforming to the Bluetooth specification version 1.1 (cf. [Blu01]). This is due to the fact that Salonidis et al. did not take the existence of two different inquiry trains (cf. section 2.1) into account. In real life the sender (performing inquiry) sometimes needs to wait for 2.56 s until it starts sending on the correct inquiry train and even gets a chance to find the other device.

The random inquiry mode process for the symmetric neighbor discovery is visualized in figure 1. We assume that the time a device stays in a phase (inquiry or inquiry scan) consists of a fixed part (min_phase) and a variable part (var_phase). In contrast to min_phase (which is a fixed value) var_phase is a random variable distributed either uniformly or exponentially. The mean value of var_phase is denoted as var_mean.

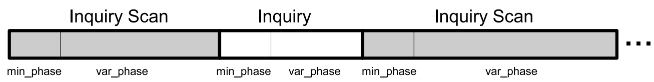

Figure 1: Random inquiry mode process.

3 Simulation Study and Experimental Results

Section 2.2 clearly showed that the symmetric Bluetooth neighbor discovery process is more complex than assumed by Salonidis et al. in [SBTL01]. According to these authors a mean neighbor discovery time of about 1 s is claimed to be achievable.

This section presents simulation as well as measurement results revealing that the neighbor discovery time with real Bluetooth hardware is significantly higher. Furthermore, optimal parameters for the random inquiry mode process (cf. section 2.2) are derived.

3.1 Scenario

The experimental setup consists of two USB Bluetooth devices from MSI which include a BlueCore02 chip from CSR with recent firmware. These devices independently switch between inquiry and inquiry scan mode according to the chosen inquiry mode process. The neighbor discovery delay is measured as the time between starting the random process on the first device and discovery of the second device by the first one.

In order to find optimal parameters, a simplified simulation environment was created that enabled us to explore a larger parameter space very quickly. This simulation very accurately models the inquiry and inquiry scan procedures of Bluetooth version 1.1 including the different inquiry trains and the random backoff. However, it does not model all the details down to the slot level which means that e.g. radio interference effects are ignored.

3.2 Results

Figure 2 shows experimental and simulation results for the mean neighbor discovery time using a uniform distribution for var_phase. The simulation model seems to match reality quite accurately. Note that the mean neighbor discovery time stays above 40 s until $\mathrm{min\_phase} + 2\mathrm{var\_mean}$ exceeds 2.56 s. This is due to the fact that in this case only inquiry train A is activated by the sender and thus only 50% of all neighbor discoveries are successful. Unsuccessful neighbor discoveries have been accounted for with 150 s in both the simulation as well as the experimental study.

Figure 3 shows measurement and simulation results with min_phase fixed to 0.25 s with the uniform and exponential distribution for var_phase. The exponential distribution performs better for var_mean between 0.5 and 2 s. This is due to the fact that the exponential distribution has no upper bound and thus train B is used in some cases even for low values of var_mean. However, for var_mean larger than 2 s both distributions show similar performances.

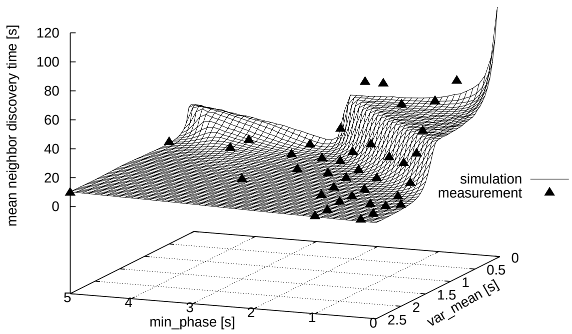

Figure 2: Mean neighbor discovery time: Simulation and measurement results.

In order to obtain best results for the neighbor discovery delay it is advisable to select a small value for min_phase (e.g. 0.25 s) and a value between 2 s and 3 s for var_mean. This yields average neighbor discovery delays of about 8 s.

4 Summary and Further Work

Simulation and experimental results for the symmetric neighbor discovery in Bluetooth ad hoc networks have been presented. It has been shown that the simulation matches reality quite accurately. The results allowed us to derive optimal parameters that lead to a mean neighbor discovery delay of about 8 s.

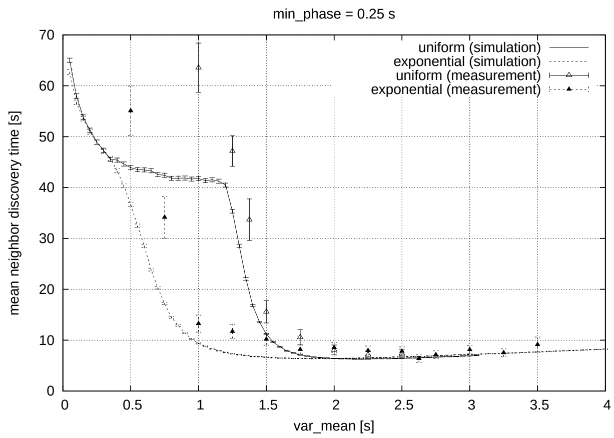

Figure 3: Mean neighbor discovery time: Simulation and measurement results for uniform and exponential distribution of var_phase.

Future work will use these results to implement and analyze automatic network formation algorithms for Bluetooth ad hoc networks. Furthermore, it will be very interesting to also study the improved neighbor discovery scheme of the current Bluetooth version 1.2 (cf. [Blu03]).

References

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