Ad Hoc Networks 25 (2015) 444–453

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

Experimental assessment of the adequacy of Bluetooth for opportunistic networks

David Contreras [a,*], Mario Castro [a,b]

[a] Departamento de Telemática y Computación, Escuela Técnica Superior de Ingeniería (ICAI), Universidad Pontificia Comillas, E-28015 Madrid, Spain
[b] Grupo Interdisciplinar de Sistemas Complejos (GISC), Grupo de Dinámica No-Lineal (DNL), Spain

ARTICLE INFO

Article history:
Received 4 March 2014
Received in revised form 19 July 2014
Accepted 16 August 2014
Available online 28 August 2014

Keywords:
Opportunistic networks
Bluetooth
Discovery
Inquiry
Interference
Interlaced

ABSTRACT

Bluetooth ranks among the most widespread technologies in current mobile devices. One of the most promising application fields of Bluetooth is that of the so-called opportunistic networks. In order to assess the validity of Bluetooth for those scenarios we perform systematic experimental tests changing the Bluetooth discovery mode, the number of devices participating in the network (up to 20) and their roles. This discovery stage is crucial for the identification of devices in the range of the network. Our results allow to conclude that in asymmetric cases (where nodes work exclusively as masters or slaves) Bluetooth working in interlaced mode can be clearly used even in the less favorable situations. On the contrary, in opportunistic networks where the nodes must change their role from passive (being found) to active (find other nodes), the higher the size of the network the higher the times needed to remain in each inquiry, so the parameters of the devices need to be set according to the application in mind. These results help to introduce alternative strategies to overcome the lack of knowledge about the entry of devices into the network range and the number of them to be discovered. Finally, we compare the effect of performing the experiments inside a Faraday cage or in a contaminated environment and that the standard network simulator (ns-2) does not capture the complexity of the experiments.

1. Introduction

Bluetooth is a widely spread technology due to its low manufacturing cost (~$1 per dongle) and support by the industry. Although conceived as a wireless alternative to basic wired devices (as headphones) it has proved versatile enough to be used for many other applications (which has also pushed forward the development of this technology through different versions of the specification).

Additional benefits of Bluetooth lay on its widespread use in smartphones, what makes it a good candidate for ad hoc networks, in general, and opportunistic networks in particular [1–4]. A simple example of its potential use is indoor positioning, in which a Bluetooth device must localize the passive *beacons* which are in a given range in a particular moment in order to determine its position. More complex opportunistic networks require all the participants to assume both active and passive roles. In general, in those scenarios, it is critical to limit the maximum time to discover a device as this reduces the opportunity window for that device to participate in the network.

In principle, the usefulness of opportunistic networks rely on the highest number of participants in the network but, as we show empirically in this work, the presence of multiple devices may be detrimental for the time needed to discover all of them. As a side effect, the overall

* Corresponding author.
E-mail addresses: davidcb@upcomillas.es (D. Contreras), marioc@upcomillas.es (M. Castro).

http://dx.doi.org/10.1016/j.adhoc.2014.08.007
1570-8705/

performance of the networks drops and, indirectly, the energy consumption of the active nodes raises [5].

In this work, we provide experimental results that allow us to characterize specifically the role of the competition for the transmission channel and the number of participants in the discovery procedure. We also provide a comparison with the standard network simulator (ns-2) and show that it does not capture the effect of noise and interference properly.

As mentioned above, in a general opportunistic network all the devices may play active (trying to discover) or passive (listening) roles. Traditionally, and in order to fully understand the performance of opportunistic networks in real scenarios, the scope is often restricted to simplified scenarios in which different participants in the network adopt different roles. However, we provide a systematic account of different experimental situations, ranging from simple controlled cases (for instance, just two devices in a Faraday cage) to more realistic situations (where all the *actors* may act actively or passively). Thus, we show that longer delays are experimented by the devices as the number of participants scale up and, more importantly, the fact that without enough time not all the devices are even discovered.

It is worth noting at this point that, although Bluetooth was conceived to allocate at most seven slaves and one master, in the opportunistic contexts the only relevant information is the presence of a device within the range of the master. In those cases the number of participants in the process of discovery is unlimited, as the piconet does not need to be created.

2. Bluetooth architecture

To fully understand what factors impact the performance of Bluetooth in the scenarios discussed in the present work, in this section we summarize, briefly, some relevant features of the Bluetooth architecture.

The Bluetooth specification [6] establishes that the inquiry procedure involves two sides, the master (*inquirer*) that will search other devices in the inquiry state and the slaves (*scanners*) which are discoverable nodes in the inquiry scan state. The master will periodically broadcast several packets devoted to this aim (ID packet) during a $T_{w\_inquiry}$ period within an interval $T_{inquiry}$ seconds. Analogously, the slave will enter the inquiry scan state each $T_{inquiry\_scan}$ seconds in order to be discoverable and to reply the ID packets through FHS packets during the $T_{w\_inquiry\_scan}$ (11.25 ms). A side effect of the time spent in the inquiry state is that the energy consumption is twice that in the idle state [7] what might impact the autonomy of the devices resulting critical in some cases.

To reduce interferences among participants, the ID packets are transmitted using 32 different frequencies divided in two groups of 16. These groups are called trains (labeled A and B) that contain 8 Low Frequencies (LF) and 8 Upper Frequencies (UF) each. In a $T_{inquiry}$ period, 4 sequences of A and B trains are transmitted in alternating order (A–B–A–B); each sequence has 256 trains. Taking into account that every train is transmitted during 16 slots (2 frequencies per slot transmitted only in odd slots) and that each slot has a duration of 625 s, the total window time in which the master can find a slave is $T_{inquiry} = 16 \times 625\ \mu s \equiv 10\ ms \times 256 \times 4 \equiv 10.24\ s$. In ideal conditions, the master will find a slave within the first two trains (A–B) of the scanner [6].

Here we must distinguish between the so called *standard* and *interlaced* modes. In the standard mode the slave will enter the inquiry scan sub-state to be discoverable and to listen master's ID packets on a frequency named as F_{scan}. Additionally, it will hop on the 32 possible frequencies taking $T_{inquiry\_scan}$ seconds to hop between two different channels. This time should not be higher than 2.56 s which is the duration of a complete sequence of 256 A or B trains. $T_{inquiry\_scan}$ is usually set to 1.28 s or 2.56 s, depending on manufacturers implementations.

On the contrary, in the interlaced mode the slave listens every $T_{inquiry\_scan}$ in two different frequencies at the same time: F_{scan} and $(F_{scan} + 16)\text{mod}(32)$.

3. Related works

In this work we focus on technological aspects of the viability of Bluetooth as a technology for Opportunistic scenarios. The interest on where those scenarios can be suitable has been recently discussed in Liu et al. [8]. Those authors, have proposed a unified framework to capture key aspects that characterize the net potential for opportunistic networks.

In the standard mode, the division of frequencies in two trains makes the distribution of time to discover a device bimodal [6], as a device will be either discovered in the first A train or in the first B train. This theoretical bimodality was verified numerically by Anastasi et al. [9] by simulating either a Bluetooth network according to the specification or an alternative which suppresses one of the trains (B). In the latter case, those authors showed how this bimodal distribution disappears. Here we adopt the same observable as in [9], namely, the cumulative distribution function (CDF) of the inquiry times (i.e., the probability of discovering n devices during the inquiry process before a given time). In the figures, we will refer to this observable with the acronym ECDF which stands for Empirical Cumulative Distribution Function.

Despite the interest on opportunistic networks and indoor positioning scenarios, the variables affecting the mean inquiry time have scarcely been studied and, in general, different approaches are either theoretical (and/or combined with non-standard simulations) or experimental involving just one slave.

Specifically, Dufflot et al. [10] used a probabilistic model to relate the discovery time with the power consumption in a system with one slave. Chakraborty et al. [11] showed how the discovery time affects the presence of multiple potential slaves by means of simulations. Their main conclusion is that the inquiry time decays exponentially with the number of slaves. However, the simulation procedure does not include the (relevant) effects of noise. Other works [12] focused on the Bluetooth 1.1 specification, in which the most relevant parameter is the *backoff*