Behavior of Bluetooth Bridging Nodes within an Adaptive Service Providing Environment

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Abstract ***In order to demonstrate our research results on managing wireless networks that are used to provide mobile services with a large spectrum of application, we developed the BlueSpot system. This system can be easily used to investigate various open questions concerning wireless networks. Here, we present results that became apparent during our investigations on Bluetooth Scatternets with the aid of the system. We demonstrate the differences of master-slave and slave-slave bridged networks and explain their diverging behavior.***

Keywords: Bluetooth scatternets, meshnets, BlueSpot system, adaptive middleware

1 Introduction

The theory behind wireless networks is growing more and more complex, triggered by new realities from the fast evolution of new communication technologies. Especially, with the recent integration of the Bluetooth technology or the IEEE 802.11 standard into cellular phones, nearly every user is able to build up short living wireless connections and to transfer data. In the near future, the trend is that these "emergent" kinds of connections will grow even more complex. They will be omnipresent in time, especially in the category of so-called wireless information networks.

In order to handle and organize connections that occur in such networks, and thus be able to form more complex wireless network structures automatically, we developed the BlueSpot system [1], [2]. This system is used to work on a large spectrum of current network technologies and mobile devices. It contains a middleware that must be installed on the device of each participant in order to integrate the device as a node into the wireless network. The middleware contains capabilities that allows it to adjust itself to the demands the mobile services, which are running on top of the middleware. As a result, adaptive behavior is integrated into the BlueSpot system.

Our main focus in the course of development of the BlueSpot system was an elaborate support of the Bluetooth standard. Therefore, the differentiation of master and slave nodes, as well as of master-slave (M/S) and slave-slave bridges (S/S), as defined within the Bluetooth standard [3], were taken over into our system's underlying network structure. During this process, it became apparent that the usage of M/S bridges in comparison to S/S bridges showed a very different behavior of the installed wireless network [4]. For this reason, we started to investigate Bluetooth Scatternets and their capabilities. The results of this investigation shall be shown in this paper. Additionally, we will demonstrate the difference of M/S and S/S bridged network and explain the fundamentals shown with our benchmarking proceedings.

This paper is structured as follows: in the following section several different types of wireless networks are classified and the BlueSpot system is ranged into this order. In the third section the benchmarking procedures we used to perform our measurements are described. The forth and fifth sections present the results gained by use of these benchmarking procedures, ordered into throughput and latency times. The sixth section provides a direct comparison of M/S and S/S bridging nodes and explains the presented differences. Additionally, we recommend which type of network should be used according to the demanded properties of the underlying network structure.

2 Related Work

State of the art wireless networks are currently in use in four fields of application. One field are wireless networks that consist of *wireless integrated network sensors* (WINS) [5]. The sensor nodes are highly integrated, and in most cases, they do not have their own power supply. They obtain their energy by induction current that is emitted from a central master.

A second field of wireless networks concerns *wireless sensor networks* (WSN) [6]. They consist of many small nodes that are organized in order to cover and observe a large geographical area. Each node contains its own logic and tries to connect to a neighboring node in order to establish a single- or multi-hop network. They are distinguished by focus: by the dedication to a specialized purpose.

The BlueSpot system presented here belongs into a third category. Wireless networks in this class aspire to provide more complex services; complexity being characterized by: 1) streaming versus message based communication, 2) critical latency times, 3) critical bandwidth, and 4) client-server communication versus peer-to-peer communication. The detailed characteristics of such services are described by Duemichen [2]. Due to their more complex requirements, the underlying hardware needs to be equipped with a larger amount of resources, and the providing wireless infrastructure needs to be managed more extensively. Since about the mid 1990s, wireless networks within this third category are named *wireless information systems* (WIS) [7]. As an early example of this type of networks that deliver services based on produced information over an elaborately organized wireless network see Gerla and Tsai [8]. The BlueSpot system provides more potential for *variety* of future mobile services (generalizability at the service level) versus potential for *volume* on the level of one special service (specialization). This laboratory work at TU Muenchen focused on as much generalizability as possible.

A fourth field of wireless networks concerns providing of infrastructures for services with a certain degree of geographical coverage and depth. In this case the type of sub-services is not explicitly specified, but is mostly tied to telecommunication services or internet providing services. Examples for this field are GSM and UMTS networks as well as IEEE 802.11 WLAN or IEEE 802.16 WIMAX infrastructures.

With our work on the BlueSpot system, we have reached a certain degree of integration that can be used to easily investigate more detailed explorations, as will be done in the following of this paper. Whereas proceedings of other research groups concentrate on the routing and scheduling issues of Bluetooth-based Scatternets [9], [10], it is important to have a fundamental understanding of the behavior of the underlying network topology. E.g. the network routing algorithm of Cuomo et al. [9] works on a tree-based network formation that mostly consists of M/S bridging nodes. But they do not take into account the resulting properties that occur due to the usage of this type of bridging node. As can be seen in the following of this paper, especially larger Scatternet formations will have a poor performance as a result of the usages of M/S bridging nodes.

3 Benchmarking Procedures

In order to understand the following benchmarking procedures in the next setions, it is necessary to explain the used benchmarking methods. These are described next in addition to their underlying BlueSpot middleware configurations.

Currently, we have three methods of performing measurements, each depending on the software configuration used for the benchmarking approach. The first bases on the measurement on the level of the protocol layer. This layer is part of the BlueSpot middleware and is resposible for routing issues (see Duemichen [2] for a complete description of the BlueSpot middleware structure). For the benchmarking process, we implemented an extra application that connects to the protocol layer of the middleware and uses its functionalities. In order to establish communication paths, the routing protocol DSDV [11] was selected.

The second way of measurement connects to the BlueSpot system on the level of a mobile service. This is achieved by use of a benchmarking service that is running on top of the BlueSpot middleware and contains predefined testing scenarios which can be executed in random order. As a result, any wanted set of functionalities of the BlueSpot system can be integrated during the measurement process. Also, any available adaptive behavior extension can be easily integrated into the measurement process, and can thus be taken into account. Here, the standard configuration of the BlueSpot system is used, which runs without any additional adaptive behavior extensions and the standard DSDV routing algorithm.

By use of the BlueSpot simulator that bases on the ns2 network simulator [12], results are gained in the mentioned third way. The simulator is connected to the BlueSpot middleware by simulating a virtual network device that is responsible for the entire communication. As a result, the Benchmarking Service can be again used to perform the measurement processes. Analogously to the second way of benchmarking, the standard configuration with DSDV routing and no other extensions is used here. But as a result of the underlying simulator, more complex scenarios can be constructed and investigated.

4 Throughput Results

The available bandwidth of a Bluetooth-based network shall be shown at first and therefore the throughput of a single connection is investigated. Early experiments have shown that the real throughput of a connection depends highly on the underlying hardware that was used. The theoretical values of 723,2 kbit/s respectively 2Mbit/s defined in the Bluetooth standard [13] were reached by none of our hardware configurations, but were near the mark (e.g. 241,331 kBytes/s = 1930,648 kbit/s). The testing results proved to depend immensely on the hardware configuration. In order to reduce the influence of the hardware, we permuted our available hardware and additionally often repeated the measurement process. Afterwards the measured values were averaged. All measurements were made on the level of the protocol layer. The results can be seen in table 1 and are illustrated as a diagram in figure 2.

All used network constellations are organized linearly. The installed bridging nodes are configured as M/S bridges (see figure 1 for an illustration). For the first set of benchmarking runs, the used topology consists of two nodes. The available hardware components were arranged randomly in order to construct different random hardware configurations. By chance, nine configurations were selected. For a detailed description of the hardware constellations see Duemichen [14].

The second set of measurement processes depicted in the second row concerns topologies with three nodes. Analogously to the first approach, different hardware components were used in a random order. Due to the few available hardware components and high connection break-up rates, only five measurement runs for this configuration could be achieved. Occurring connection break-ups can be

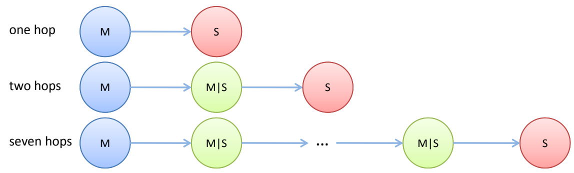

Figure 1: Network constellations used for the throughput measurements

explained by the overlapping of many Piconets. In this configuration the resulting topology contains four Piconets (one master, three M/S bridges and one slave) that disturb each other immensely. The moment the influence of other Piconets grows too high, some of the connections within a Piconet will break up. The reestablishment of such connections is tried by the BlueSpot system automatically, but cannot be guaranteed. That way, the BlueSpot system tries to minimize possible system failures and to enhance its stability. Unfortunately, this falsifies our measurement results, therefore, the best results were selected here.

Instable connections are even more relevant for the third measured network constellation. This one includes eight nodes. Due to the use of M/S bridges, the network consists of seven Piconets. The moment these Piconets overlap each other, steady connections cannot be assumed anymore. Due to this, only one successful measurement could be achieved that yields an acceptable outcome. The results of the three test assemblies are depicted in a diagram depicted in figure 2.

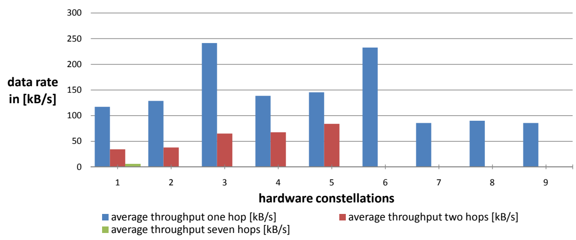

Figure 2: Throughput measurements for one, two and seven hops

The results of the one-hop network are displayed by blue bars, while the results of the two-hops and the seven-hops measurements are marked as red and as green bars. It can be seen that the results of the one-hop configurations vary very much according to the throughput rate. Especially, during the usage of the hardware constellations three and six, the achieved data rate was nearly twice the data rate of other constellations.

	1	2	3	4	5	6	7	8	9
one hop	117,0759	128,604	241,331	138,433	145,318	232,442	85,594	89,866	85,672
two hops	34,183	37,761	65,065	67,559	83,892				
seven hops	5,242								

Table 1: Values of throughput measurements based on the protocol layer in [kB/s]

When comparing a one-hop scenario to a two-hop scenario, the throughput rate decreases dramatically. Furthermore, taking the seven-hop scenario into account, the throughput rate drops to approximately 5 kilobytes per second, which is very low. This high decrease can be explained by the bad scalability of M/S bridged network and is discussed in section 6 in more detail. As a result, the establishment of a Bluetooth-based Scatternet with seven or more nodes that is based on M/S bridges can be made but comes along with the restriction of a very low data rate. Therefore, long communication paths should be avoided.

5 Latency Times Results

This section presents measurements concerning the average latency times in comparison to the hop rate. The hardware dependency is put into perspective by averaging over a random selected set of hardware configurations and a high rate of iteration of the benchmarking processes. The used network topology also bases on M/S bridging nodes, where the nodes are ordered in a linear manner. All benchmarking processes were made by use of the protocol layer. The gained results are shown in table 2.

The table contains the average values as well as the corresponding maximum and minimum values for each performed measurement process. The results of applied network configurations with two to six nodes are depicted in figure 3.

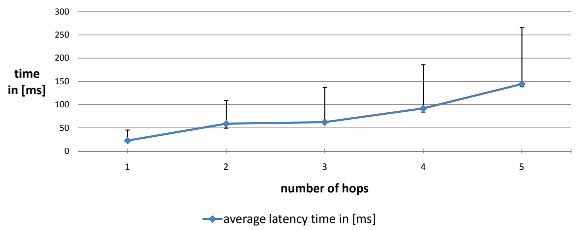

Figure 3: Comparison of latency times in comparison to the number of hops

The results depicted in the graph show that the average latency time increases in relation to the number of hops, as expected. The interesting result in this measurement process is the large interval between the minimum and the maximum measured latency times. The more nodes are involved in a communication path, the larger the possible interval of latency time is. Especially in constellations with five or more nodes, the interval grows so large that it becomes quite difficult to make any statement of particulars describing the quality of the underlying communication path. Mobile services with high demands according to their maximum allowed latency time can be impaired due to these results.

6 Direct Comparison M/S vs. S/S Briding Nodes

Considering a Bluetooth-based Scatternet with nodes in a linear order, this Scatternet can be constructed in two different ways. On the one hand, it can be established by use of M/S bridging nodes, on the other hand, the occurring Piconets are bridged by S/S nodes. Both configurations have advantages and disadvantages which will be investigated next.

In order to start our investigations, we made some measurements with the aid of the Benchmarking Service. Therefore, two M/S bridged and two S/S bridged topologies were used, each with two different hardware constellations to relativize the influence of the hardware (as it was described in section 4. The gained throughput results can be seen in table 3. For a better understanding, the underlying topologies are depicted in figure 4.

	S/S 1	S/S 2	M/S 1	M/S 2
two hops	13,7	17,1	55,8	59,1
four hops	13,1	16,2	7,8	6,9

Table 3: Throughput comparison of a S/S and a M/S bridged Scatternet in [kB/s]

The first topology depicted in the upper row of the table consists of three nodes. In the S/S bridged constellation, the nodes on the ends are masters, whereas the node in the middle is the S/S bridge. As a result, the network consists of two Piconets.

	$1hop$	$2hops$	$3hops$	$4hops$	$5hops$
average	22,345	58,806	62,145	91,785	144,341
maximum	45,356	108,459	137,2	185,67	265,563
minimum	20,943	49,491	59,873	83,833	138,457

Table 2: Latency times measurements based on the protocol layer in [ms]

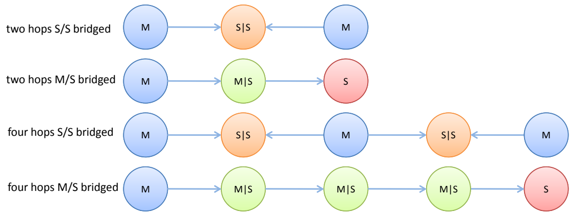

Figure 4: Network constellations for the comparison of S/S bridged an M/S briged Scatternets with two and four hops

The M/S configuration is constructed of a master, a M/S bridge in the middle, and a slave node, and thus also includes two Piconets.

The second row of the table shows the results of the four hop measurements. The S/S bridged networks consists of five nodes: three master nodes and two S/S bridges in alternating order. Therefore, this configuration contains three Piconets. For the M/S bridged network, one master, three M/S bridges, and a slave are used. In comparison to the S/S configuration, this constellation consists of four Piconets, which is one more than S/S bridged networks with the same amount of nodes have. For a better presentation, the values are illustrated in a diagram in figure 5.

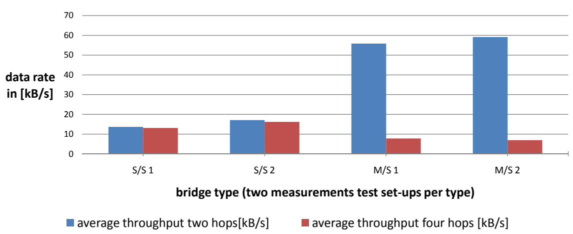

Figure 5: Throughput comparison of S/S and M/S bridged Scatternets

The blue bars mark the measurements with two hops, whereas the red bars present the results of the four hop scenarios. Apparently, the measurement of M/S bridged Scatternets with only two hops provide a much higher throughput than the corresponding S/S bridged constellations. But with the increasing amount of hops, the throughput rate drops rapidly. Contrary to this, the S/S bridged networks with few hops have a lower throughput, but the rate remains almost constant with an increasing number of hops. As can be seen in the diagram, the Scatternets with S/S bridges and four hops provide a higher data rate than those with M/S bridges.

In order to confirm this result, a further measurement approach was made. Four different network constellations were compared to each other. The formations are illustrated in figure 6.

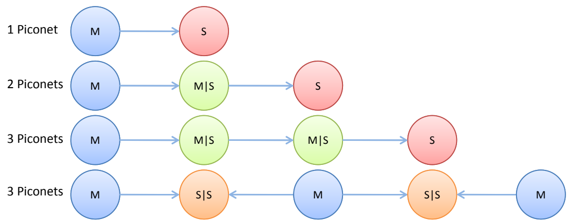

Figure 6: The four different network topologies of this measurement

The first constellation is a simple Piconet. The measurement results for this Piconet are added in order to gain comparable values of a simple hop within a Piconet and hops over a bridge. The second and the third constellations are M/S bridged networks, where the first contains one bridging node and the second contains two. Hence, the first constellation consists of two Piconets and a two-hop path in length, whereas the second includes three Piconets and three hops. The fourth scenario consists of a S/S bridged network that is also constructed of three Piconets, but due to the S/S bridges, the communication path has a length of four hops.

The aim of this measurement is to compare the throughput and the latency times with the amount of Piconets and the used type of bridging node. In the course of this measurement, various testing runs were made with different packet sizes. Afterwards, the results were averaged to one value for each network constellation. By doing so, the dependency on the packet size is eliminated. All results are gained by use of the Benchmarking Service. The throughput-measurement results are presented in figure 7.

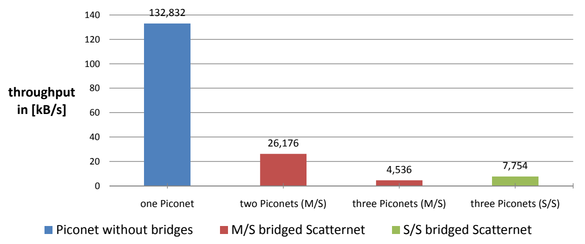

Figure 7: Average throughput comparison of S/S and M/S bridged networks

The diagram shows the throughput rates of the four different network constellations. The used packet sizes were 10kB, 50kB, 100kB, and 500kB, and they were averaged afterwards. The first entry on the left side, depicted as the blue bar, presents the throughput rate of the single hop within a Piconet. The next two bars, in red, illustrate the two M/S bridged networks, whereas the green bar shows the measured throughput of the S/S bridged network with four hops.

When comparing the third and the fourth values, it can be seen that the S/S bridged network provides a higher throughput than the M/S bridged one, while they both consist of the same amount of Piconets. Furthermore, the measurement of the S/S bridged network was made over one more hop. In addition to this, the results of the corresponding latency time measurement are presented in figure 8.

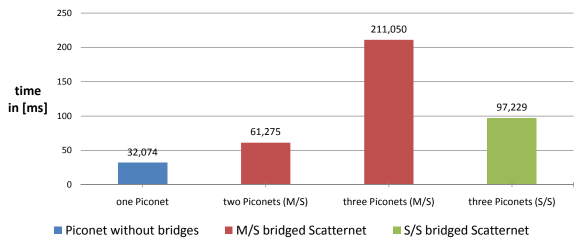

Figure 8: Average latency time in comparison of S/S and M/S bridged networks

Analogously to the throughput results, the S/S bridged network behaves better than the M/S one. As a result, the latency time is lower even though the measured communication path is one more hop in length.

In order to explain these results, various properties of the Bluetooth standard must be considered. To begin with, it is obvious that the throughput of a Scatternet with a small amount of Piconets provides a much higher throughput and much better latency times than a S/S bridged Scatternet of the same size. But with an increasing amount of nodes, the throughput rate of a M/S bridged network decreases rapidly in relation to the amount of nodes, whereas the throughput of a S/S bridged network remains near-constant, as seen in figure 5.

A bridging node can only be in one Piconet at a time, as described in the Bluetooth standard [3]. In order to transfer data to the other Piconet, it must switch its mode to *hold* in the one Piconet and resynchronize to the other. In case this bridge is a M/S node, the resynchronization process happens very fast, as it is the master that provides the clock signal for this Piconet. In case of a S/S bridge, the node must wait until it has received the required synchronization signal from the master. But this is time consuming, and as a result, the latency time increases and the throughput decreases. The large difference concerning the throughput and the latency times of small Scatternets can be explained by this.

But, in order to explain the behavior of larger Scatternets, the amount of occurring Piconets must be taken into account. As seen in the previous measurement process, the amount of Piconets has a great influence on the quality of the network. By establishing a Scatternet on the basis of S/S bridges, a Piconet always contains two hops - from the S/S bridge to the master and furthermore to the next S/S bridge - whereas a M/S bridged Piconet contains only one hop - from one M/S bridge to the next (see figure 6). The latter results in networks with a larger amount of Piconets. Considering the previous measurement results of one hop within a Piconet, the throughput was at least six times as high as the rate of a M/S bridged network with two hops (first and second values of figure 7). By additionally taking into account that all S/S bridged Piconets contain two internal hops, the disadvantage of the worse performing S/S bridge is balanced out.

Another advantage of the S/S bridged network is the capability of this kind of network to maintain connections to other slave nodes, whereas in a M/S bridged network, a Piconet is closed to communication if the master node is switched to the other Piconet. If more than one node communicates via the master node, its communication paths can be kept upright, whereas in M/S bridged networks, the same paths would be interrupted.

Based on these facts, it is obvious that networks that run services which require short communication paths should be constructed on basis of M/S bridges. But if services are run on top of a network that requires communication paths that are longer than two hops, the underlying network should consist of S/S bridged Piconets.

7 Conclusion

In this paper we presented measurement results made by use of the BlueSpot system. This way, we were able to demonstrate that our system is working and can easily be used for the investigation of open questions concerning wireless networks. We could show that the throughput rate of Bluetooth based Scattenet greatly depend on the used hardware as well as on the configured network constellation.

Subsequently, we presented measurement results for the latency times of multi-hop Scatternets. Here, we managed to show that beside the used packet size for data transmission, again the selection of the best fitting bridging type is of great importance. By comparing measurement results made for M/S bridged as well as for S/S bridged Scatternets, we explained the differences of these two types and were able to recommend which one should be used for future Scatternet constellations.

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