Performance Evaluation of a Link Consolidation Mechanism in a New Scatternet Formation Protocol

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Abstract: - Bluetooth technology allows the use of WPANs where cables have been replaced by temporary radio connections between the different network devices. The goal of this paper is to present and evaluate a new scatternet formation algorithm that makes it possible to communicate between nodes that are not close enough to communicate directly using Bluetooth. The algorithm gives a reliable and strong network topology where several paths can be found between every two different terminals. In addition, the degree of connectivity between network terminals can be controlled by setting the parameters of the proposed link consolidation mechanism. The analysis of this new method has been made using values acquired by simulation and following scatternet quality indicators.

Key-Words: - Bluetooth, WPANs, scatternet, formation, connectivity, performance.

1 Introduction

Although the main and most common use of Bluetooth technology is for replacing cable connections among different units by radio connections to achieve a wireless local area network, this technology can also be used to build a wireless wide area network. The results of this is an ad hoc network, called a scatternet, formed by the interconnection of several groups of connected nodes, and these smaller groups are known as piconets. The members of a piconet share the same channel, and there is a master node that controls all the parameters needed to grant or deny access to the other nodes that become slaves in the piconet and have to be synchronized with the master node using this channel. The several existing piconets can be joined to get scatternets, and a node can acts as the master in one and as slave another. When there are several Bluetooth devices in the same coverage area, there is not only one possible network solution, but rather many different scatternets can be formed, depending on the design parameters and criteria. Many scatternet design algorithms can be found in the literature and each one gives a different network formation topology. Some of these methods need all the nodes to be in the same coverage area [1] and some other can be applied to wide networks. In case of a node can not reach all the other nodes in the network, intermediate units will be necessary to let a node communicate with another one. In relation to the topology, firsts papers presented scatternet where tree based structures are used[2]. This topology is not very strong. Since if a node fails the whole sub-network will be unreachable from a top node, other scatternets topologies, such as those based on rings [3] or stars [4] have been developed and analysed by simulation.

In this paper a new scatternet formation algorithm is shown and its performance is evaluated, showing that starting with a set of Bluetooth devices situated along a wide geographic area, a strong and reliable network can be built; and the degree of connectivity between terminals can be controlled by a proposed link consolidation mechanism. The following section introduces the new scatternet formation algorithm, while section 3 tests the resulting networks according to some scatternet quality indicators and shows the different simulation results. The last section presents conclusions about the performance evaluation of the new proposed algorithm.

2 Network Formation Algorithm

This new scatternet formation algorithm is based on the need for a strong and reliable network, where there are at least two different paths to get from one node to another in the network. The ability to control the degree of connectivity is also very important,
because in situations where the same node is switching back and forth between different roles (master and slave) and there are too much piconets in the same area the packet collision rate will increase and the risk of interference will rise [5]. Furthermore, if the number of links of a terminal is too high, this node will have to spend too much of its resources just in maintaining its links and there will not be enough resources for communicating or carrying out any other important job the node has to perform.

2.1 Setting up new links
The fact that two Bluetooth devices are close in proximity does not mean that they are connected. They need to find each other and, following an existing protocol, a new link has to be created after they decide which channel they will use. Although the mechanism to set up a link between two nodes is defined [6], before starting each unit must decide the role that it will have in the new connection: the master node (the main node, which will start the connection, passing through the ‘Inquiry’ and ‘Page’ Bluetooth modes) or the slave node (which will wait for the other to start the procedure and will pass through the ‘Inquiry Scan’ and ‘Page Scan’ Bluetooth modes).

A symmetrical protocol can also be used to create a new link; and nodes do not have to decide their role before creating the link [1]. The problem with this method is that units using it will not have enough time to perform any other tasks, such as network maintenance or information sending or receiving.

The proposed mechanism makes it possible for units to have time left over not only for keeping their connections active or building the network, but also for communicating, sending and receiving data, or carrying out any other task they need in order to perform their assigned jobs.

To set up a new link, each unit will change periodically to a specific state over a given interval of time (T_{Tx}). While in this state the unit will try to set a new link as master.

Moreover, the unit will change periodically to a complementary state over a different given interval of time (T_{Rx}). In this case, the unit will try to become a slave. Terminals will keep in this state at least for 10ms (16 slots), to ensure they attend incoming messages from the nodes that are trying to set a new link as master. By using this mechanism, when two radio electric neighbours find each other in complementary states, a temporary new link will be created.

Figure 1 shows the different states used by the nodes in the network to set up a new link. During ‘Tx’ slots the unit will try to become the master and during ‘Rx’ slots the unit will try to become the slave.

![Fig. 1. Link creation states.](image)

2.2 Link consolidation mechanism
The procedure used by the units to create the new links has not limits on the number of links that a unit can set up. Even every two units could be connected by a new link. In order to improve this fact, a control mechanism is necessary to control the degree of connectivity in the network. Some new links will be destroyed, those that made up closed rings formed by a number of nodes that is equal or smaller than a given number. This parameter of the algorithm is known as loop_length.

When two terminals decide to set up a new link, they mark it as provisional. After that, they check if there is a path between them whose length was equal or smaller than the loop_length. In this case, the provisional link will be destroy. With the suitable selection of this parameter the degree of connectivity in the scatternet can be controlled to modify the resultant network topology.

In order to check alternative paths, the nodes will send a packet, called a local token, to all its connected nodes. The local token is a special packet, with a time of life field, that will be initialized with a value that will depend on the desired length of the path that the local token will follow. This value will be given by the loop_length parameter, so it will allow longer or smaller paths.

When a new provisional link is created between two terminals, the unit which has established a lower number of links sends the local token. The other unit starts a countdown timer that is initialized with a value that depends on both the loop_length parameter and the packets delay due to retransmission along intermediate nodes of the network. If the second node receives the local token while the timer still goes, it means it exists an alternative path between these two terminals whose length is equal or smaller than the loop_length parameter, so the provisional link will be destroyed and no longer used. On the other hand, if the timer expires before arriving the local token the provisional link will be consolidated.

The value of the timer must be high enough to let the local token arrive before the timer expire if the length
of the path is equal or smaller than loop_length parameter. But also, it must be low enough to let the timer expire if the path is longer.

Figure 2 shows an example of the way the link consolidation mechanism works. In that figure, the links between the nodes in the network are represented by arrows, from each master to their slaves. In this example, the nodes 17 y 22 establish a new provisional link. In this way, the nodes 17, 22 and 18 will form a loop whose length is 3. Because of the loop_length parameter has been initialized with 3, after a period of time the new provisional link will be destroyed. However, longer closed paths will continue existing, as the loop that is formed by nodes 19, 24, 4 y 25, whose length is equal to 4, or the loop that is formed by nodes 5, 6, 7, 11 y 10.

2.3 Network maintenance

Until now, only the network formation and growing tasks have been considered, but terminals have also to spend some time in maintaining the links they already have created, because of the link supervision protocol described in the specification has to be followed [6]. It will be necessary to carry out an optimal scheduling of the different tasks that each unit must perform. In this way, each terminal must keep a list of pending tasks that have to be attended in a specific period of time. Each task has assigned a duration, and due to a node can only be active in a piconet at a time, two different tasks can not be overlapped in time.

The different tasks a terminal can perform are: the establishment of new links as a master or as a slave, sending and receiving information, and the maintenance of one of its established links. During some periods of time the unit may have no specific task to do, so it will not be active and will be in ‘Hold’ mode. In this Bluetooth mode the unit will need much less power than in others, such as ‘Connection’, ‘Inquiry’, ‘Inquiry Scan’, ‘Page’ or ‘Page Scan’.

When two nodes have set up a new link, each time they communicate they must decide the period of time that link will stay in ‘Hold’ mode. This interval of time will be the period from that communication between these nodes and the next one. In order to calculate that interval the list of pending tasks of each node will be considered. The value will be fixed to the next period of time in which they have a free slot window to attend that link. There is a suggested time, that is known as t_hold parameter. The units will try to set their hold time as close to this parameter as they can.

If this t_hold parameter is set up very close to the technology limit, 40.9 seconds, the units will stay almost all their time in ‘Hold’ mode, and this will result in a saving energy technique. However, the network will have a low data transmission rate. It is very important to select an appropriated value for this parameter that allows to save energy but also a high data transmission rate.

Figure 3 shows a task scheduling example for three different Bluetooth units in the same network. Some different slots can be seen. They are used for each unit to attend to their different tasks. Some slots are used for data transmission between the nodes which identifier appears inside each window as a number. The time slots that are marked as ‘Tx’ and ‘Rx’ are the intervals of time used by the nodes to set up new links as master or as a slave, respectively, as we explained before, in section 2.1.

In this particular case, the unit 1 starts trying to become a master in a new link. While this interval of time the unit 1 is waiting for any other node that is trying to become a slave. The unit 2, just after creating a new link with the node 3, answers to the unit 1. During the link establishment process the unit 2 has enough time to carry out another tasks. So the units 2 and 3 can communicate to each other before a new link between the nodes 1 and 2 was set up. After
that, the connection between the nodes 1 and 2 is consolidated and they will negotiate the interval of time until their next communication. Following the proposed task scheduling mechanism, both terminals will try to set this interval as close as possible to the $t_{\text{hold}}$ parameter. However, since the unit 2 must also communicate with the unit 3, both units 1 and 2 will have to negotiate a shorter period of time, just to let the unit 2 to attend both links.

3 Algorithm Evaluation

In order to evaluate the topology and performance of the scatternets that have been formed by the algorithm described in the preceding section, we have developed a simulator by using Visual C++ 6.0. In the simulated scenarios, we have considered a grid of $n$ Bluetooth nodes that have been located in a geographic area. Each unit is supposed to be able to communicate just only with its 8 nearest neighbours. The number of nodes that will form the scatternet and the value of the loop_length parameter have been modified along our simulations. The aim of this is to analyse the effect of the link consolidation mechanism on different parameters that are often considered to be indicators of the quality of the network\cite{[4]}[\cite{7}].

![Fig. 4. Average number of piconets.](image)

Figure 4 shows the average number of piconets in the generated scatternet. As we should expect, this number increases with the number of units, since in a bigger network the nodes will be grouped into a higher number of piconets. The link consolidation mechanism only seems to improve the level of this indicator in wide networks.

The average number of slaves per piconet is depicted in Figure 5. As can be seen in all cases this number is under 7 that is the maximum number of slaves that can be active at the same time in a piconet. Thanks to this, Bluetooth mode ‘Park’ is not needed and the master node will not have to spend time in setting its slaves to this mode. Furthermore, if this mode it is not used slaves will not continue for an indeterminate period just only waiting to receive synchronization packets from the master. In this figure also can be seen that if link consolidation mechanism is not active the average number of slaves per piconet rises as the number of nodes increases, whereas if the mechanism is working this average becomes stable. Besides, since the average number of slaves in each piconet is lower the master will have more time to communicate with each one of them.

![Fig. 5. Average number of slaves per piconet.](image)

One of the most important parameter to take into account is the average number of roles (master or slave in different piconets) assigned to each unit, in other words, the number of piconets in which one node participates. Since nodes can be active only in one piconet at a time a high number of roles per unit translate into reduced throughput performance. Moreover, if a device is connected to multiple piconets these piconets will use different frequencies most of the time: their hop selection and timing are independent of each other. In fact, this is the reason why after a piconet switch a unit has to wait up to two slots not available for communication. As a result, piconet switches should not happen too often. Figure 6 shows that the link consolidation mechanism improves the average number of roles per node, although when loop length increases this reduction is not so significant.
Bluetooth specifications does not limit the number of connections that a terminal can establish. However, due to link supervision protocol [6], each link must be attended before a specified maximum time and as each unit has to share out its time among all its links the less links the unit has the more time for each link will have.

Without the link consolidation mechanism the average number of links per node rises while number of nodes in the scatternet increases, but if the mechanism is working this average is lower and it becomes stable, as Figure 7 shows.

Figure 8 shows the average shortest path length between any two nodes of the scatternet. The results are compared with the visibility graph that represents the network that would be created if every node established a link with all devices that were in its transmission range.

Two slaves, even if they are radio electric neighbours, can not send or receive information directly. All communications inside a piconet must go through the master, and this fact increases the length of the paths in comparison with the visibility graph. Moreover, organisation based in piconets interconnection forces to the nodes, which are very close in the visibility graph, to communicate along the scatternet using longer paths. Those paths may pass through different piconets. The less degree of the connectivity between the nodes is, in a given network topology, the more different it will be the from the visibility graph and the longer average length path between the nodes will be. This fact is shown in Figure 8. If the loop_length parameter is increased then the average shortest path length also increases. The greater this parameter is, the less degree of connectivity will be in the network and the better are the other scatternet quality indicators. As can be observed, a proper selection of loop_length parameter is necessary in order to satisfy all the network requirements.

4 Conclusions

In this paper, a new Bluetooth scatternet formation protocol has been introduced and evaluated. The algorithm can work with dynamic environments, that is with devices joining and leaving the scatternet, and support fault tolerance.

The protocol generates connected scatternets with multiple paths between any pair of nodes without requiring the Bluetooth devices to be all in each other transmission range. The algorithm also allows to control the degree of the connectivity in the network
by the proposed link consolidation mechanism. This mechanism makes it possible to form a reliable and strong network topology with a good performance.

A simulator has been developed to address all the details pertinent to scatternet formation. The performance evaluation allows us to analyse metrics of the quality of the networks both when link consolidation mechanism does not work and for different degrees of the connectivity in the network. As the simulation results show, the link consolidation mechanism improves almost all of scatternet quality indicators. The best results has been obtained when the degree of the connectivity is lower. However, even in this case the average shortest path length between every couple of nodes is acceptable.

References: