Algorithms for Ad-hoc Piconet Topology Initialization

Evaluation for the IEEE802.15.3 High Rate WPAN System

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Abstract—**This paper deals with piconet topology issues in IEEE802.15.3 High Rate Wireless Personal Area Network standard. These issues preventing two devices to establish a connection come from the coexistence of two conflicting concepts: ad-hoc networking and centralized coordination. An algorithm for the initialization of the topology of the piconet is proposed. This algorithm leads to a probability higher than 95% of connection success in the whole power emission range defined by the standard**

Keywords-WPAN; ad-hoc; topology; piconet; IEEE802.15.3

I. INTRODUCTION

In the rapid evolving wireless networking domain, two types of networks remain discernible. The first type is designated as infrastructure-based i.e. with fixed access points that allow transmission between wireless stations within a cell. The second type is designated as ad-hoc networks since these networks do not require pre-deployed infrastructure. Each wireless device is capable of transmitting directly to another wireless device in range.

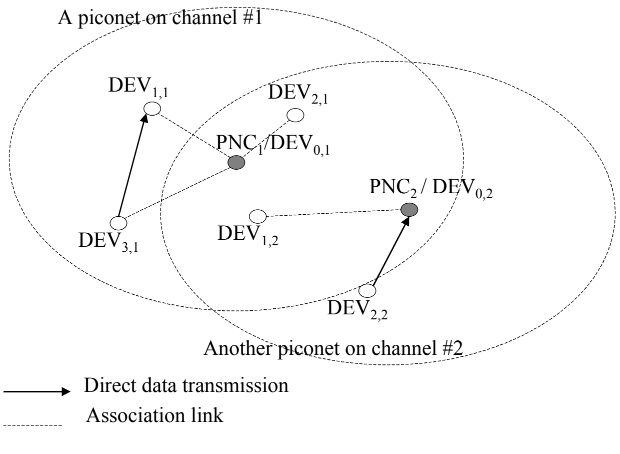

Figure 1. Typical 802.15.3 Network Topology

Piconets are an instance of such networks. A piconet can roughly be considered as a ten-meter radius sphere that envelops a device either stationary or in motion. It allows communications to be established spontaneously between devices located in this sphere [1]. Because Wireless Personal Area Network (WPAN) does not need more than short-range connectivity but self-organization, several WPAN standards use such architecture that introduces ad-hoc features in a piconet. The most popular WPAN standard is based on the IEEE802.15.1 – Bluetooth™ standard [2]. In this paper, we focus on the IEEE802.15.3 standard for High Rate WPAN [3] because it offers attractive features like high data transfer rate (up to 55 Mbit/s), QoS provisioning and uses the worldwide available 2.4 GHz ISM unlicensed frequency band. Like Bluetooth™, the IEEE802.15.3 piconet topology is based on the master/slave paradigm e.g. an elected device is responsible for coordination in the piconet. Introduction of a coordination function on an elected device in an ad-hoc environment raises several questions: How can the coordinator be elected? How can the piconet topology be initialized?

After a brief presentation of IEEE802.15.3 High Rate WPAN standard, the main topology issues preventing connection establishment between two devices are depicted. Next, algorithms developed for ad-hoc topology initialization are proposed. Then, they are evaluated by simulations considering a set of devices in which these algorithms and 802.15.3 capabilities have been implemented. Evaluation is based on the probability that two devices that are randomly chosen succeed in exchanging data. Results and possible improvements are discussed. At last we conclude and expose the further works.

II. IEEE802.15.3 STANDARD OVERVIEW

In current section, we briefly present the IEEE802.15.3 standard. First a typical piconet topology is described. Then in a phenomenological approach, the way a device can enter the network is presented: it can set-up its own piconet. Otherwise, it can associate to an existing piconet. At last, the manner a given device can get out a piconet is also presented.

From now, the term piconet is used instead of IEEE802.15.3 piconet except if explicitly said. Piconet is the basic topology used in the IEEE802.15.3 system. A typical 802.15.3 network topology is depicted in Figure 1. Piconet topology is based on the master/slave paradigm firstly introduced by the Bluetooth™ system. Here the master device is named PicoNet Coordinator (PNC) and slaves are simply designated as simple DEVices (DEV). A piconet encompasses exactly one PNC and up to 236 DEVs. Two DEVs included in the same piconet can exchange data directly. Four co-located piconets can operate without interference in the 2.4 GHz frequency band thanks to the set of four channels that is defined. Two piconets and one IEEE802.11b [4] system can coexist without interference in the same area thanks to the three-channel set defined for this purpose. In Figure 1, there are two co-located piconets. They are set-ups on two different channels. PNC_1 and PNC_2 coordinate the piconets on channel #1 and channel #2 respectively. Because $DEV_{1,1}$ and $DEV_{3,1}$ belong to the same piconet, they can exchange data; similarly for $DEV_{2,2}$ and $DEV_{0,2}$ (which is also PNC_2).

A DEV that wants to become PNC must follow four steps. First, the DEV scans all available channels. Second, it chooses a free channel. Third, it stays listening to the selected channel for a period of time to be sure channel is free. And finally, if selected channel is free, the device becomes PNC and starts to broadcast beacons.

Within a piconet, time is divided into superframes. Typical scheme of a superframe structure is shown in Figure 2. A superframe is made of three parts. First part is the beacon. The beacon allows DEVs to synchronize to a piconet and contains piconet information (piconet identifier, superframe duration, and channel time allocations). The second part of the superframe is the Contention Access Period (CAP). The CAP can be used for signaling messages as well as small data transfers. Channel access in CAP is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). Third part is the Contention Free access Period (CFP). Channel access in CFP is based on TDMA (Time Division Multiple Access) mechanism. CFP is divided into slots named Channel Time Allocation (CTA) slots. CTAs can be used for commands transmitted to or from the PNC (MCTA – Management Channel Time Allocation slots) or for data (CTA). CFP slots are managed by the PNC. Size of the CAP and CFP may vary according to channel time needs and the CAP can be replaced by exclusive use of MCTAs.

Beacon	CAP	Contention Free Period						
		MCTA 1	MCTA 2	CTA 1	CTA 2	…	CTA n-1	CTA n

Figure 2. Superframe Structure

If a device wants to establish a piconet and finds all the channels busy, it can request an established piconet to create a dependent piconet. A dependent piconet requires a time allocation in another piconet (parent piconet) and is synchronized with the parent's timing. They are two types of dependent piconets. First, a child piconet is a dependent piconet where the PNC is member of the parent piconet. Second, a neighbor piconet is a dependent piconet where the PNC is not member of the parent piconet. A parent piconet with a child piconet are shown in Figure 3. In this figure, there are two piconets. Parent piconet and child piconet operate over the same channel. There is a reserved period of time in the parent superframe (respectively child superframe) that allows child PNC (respectively parent PNC) to broadcast its beacon allocate its own CAP and a CFP. A DEV included in child piconet (respectively parent piconet) can not exchange data directly with a DEV in parent piconet (respectively child piconet) except if it belongs to the two piconets. An example is provided in Figure 3 via DEV_4, which acts as an ordinary DEV in parent piconet and as PNC in the child piconet.

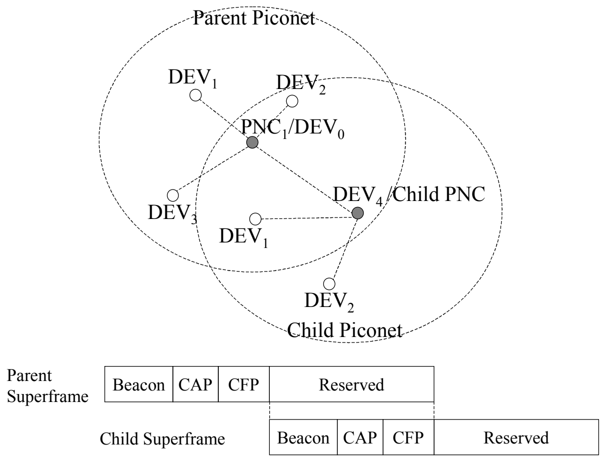

Figure 3. Parent and child piconet

If a DEV wants to be included into an existing piconet, it has to follow three steps. After scanning all the available channels, it must select a channel where there is an established piconet. Finally, it joins the selected piconet by sending an association request. Once a DEV is associated, it can request channel time to exchange data by sending a message request to the PNC. The PNC decides to satisfy the request if there are enough available time in superframe. If a DEV needs channel time on a regular basis, it makes a request to the PNC for isochronous channel time. If a DEV needs to transfer an amount of data, it makes an asynchronous channel time request for a total amount of time to be used to transfer its data. The standard offers three modes of acknowledgment: no-acknowledgment, immediate- acknowledgment and delayed-acknowledgment. In the first mode, the frames are not acknowledged and in the second mode, when a frame is correctly received the recipient immediately replies with an acknowledgment frame. In the last mode the recipient may differ acknowledgement frame after reception of a burst of data. If current channel conditions are not satisfactory, the PNC can operate a channel handover.

If the PNC decides to stop its piconet, it can operate a PNC handover. If no PNC-capable DEV is found in current piconet, it simply stops to broadcast beacons. A PNC handover can also be performed at any time i.e. when a new DEV joins the piconet. DEVs can leave a piconet at any time by sending a disassociation request to the PNC.

III. Topology Issues

The piconet coverage space is defined by all the positions where a DEV can listen and correctly decode the beacon. If a

DEV can correctly decode the beacon, it may want to associate to the piconet. The piconet topology is simple but we show in this section that it suffers some drawbacks: depending on the way the piconet was formed, two devices that are within transmission range from each other may be unable to establish a communication. Firstly let us define a usage scenario, where two DEVs are considered. One DEV, the initiator, wants to communicate to another DEV, the recipient. The initiator knows the identity of the recipient. The recipient does not know the identity of the initiator and it does not know that a DEV wants to establish a transmission with it. Without loss of generality, let us also consider that only two channels are available to establish a piconet. Note that in practice, this case happens when an IEEE802.11b system is already present in the area.

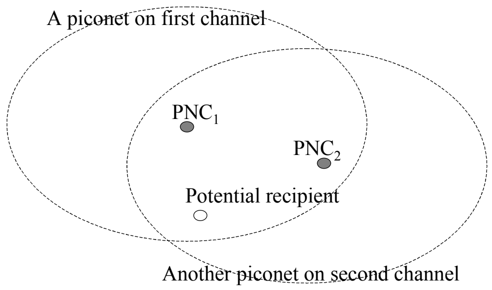

Figure 4. Recipient choice topology issue

Three examples of typical topology issues are developed in this section. Let us consider the case of a potential recipient that performs a scan and detects more than one piconet. Which piconet the DEV must choose? And before that, must the DEV really associate to one of them at this moment? This topology issue is illustrated in Figure 4. Figure 5 depicts a second topology issue that is slightly different from the first one. Here, the initiator DEV enters in an area where all channels are busy. It detects more than one piconet and it can not establish its own piconet. How can the initiator DEV choose a piconet to maximize the probability that the recipient DEV will be also able to detect it? Finally, another topology issue (see Figure 6) may occur when the initiator is associated to an existing piconet that the recipient DEV is unable to detect.

IV. Algorithm Proposal for Ad-hoc Piconet Topology Initialization

In the former section some topology issues have been pointed out. In this part we propose algorithms that aim at preventing such issues. Still, we consider a couple of DEVs. One of the DEVs, the initiator, must establish a communication with the other DEV, the recipient. The proposed algorithm is composed of two parts. The initiator DEV executes the first part. The recipient DEV executes the second part.

First part is composed of four steps.

1. Initiator DEV performs a channel scan
2. If there are available channels, initiator DEV create its own piconet, otherwise it joins with the piconet for which the signal noise ratio (SNR) measured on the beacon is maximum
3. Initiator DEV requests PNC (that can be itself) to introduce an information element in the beacon to inform recipient DEV.
4. Initiator DEV starts a timer and waits for recipient DEV association. On timer expiration the connection try is considered as failed else if recipient DEV joins the piconet, the connection try is successful

Second part is composed of two steps.

1. Recipient DEV performs a channel scan
2. If a piconet is detected that carry an information element concerning itself, it associates to it, else it starts another channel scan

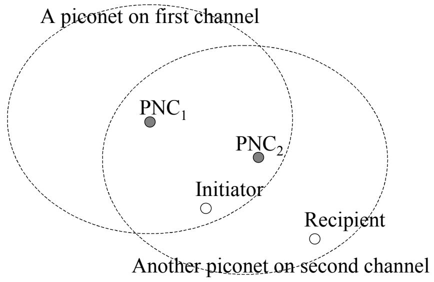

Figure 5. Initiator Choice Topology Issue

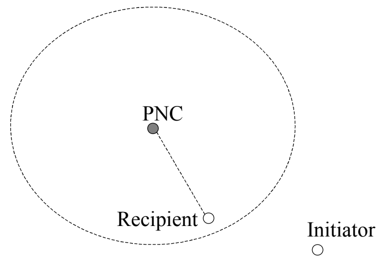

Figure 6. Out of Range Piconet Topology Issue

V. Results and Discussion

In this part the proposed algorithms are quantitatively evaluated. Evaluation is based on the probability that a connection successfully sets up between two devices and data can be exchanged. This probability is computed by simulation. Simulation consists in a large number of drawings of couples of devices that try to connect each other according the suggested algorithms. Both devices of each couple are drawn as follows. An initiator DEV of connection is randomly elected from a set of 30 randomly distributed devices over a 30*60 meters rectangular area. The other device is also randomly chosen in a 10 meters range area around the initiator. A ten meters operating range is one of the requirements an IEEE802.15.3 system must meet. Then, each DEV runs the piconet initialization algorithm as described above. The connection success event is defined as follows. When the initiator of connection joins a piconet or establishes its own piconet, it waits a time long enough to allow the recipient DEV to scan channels and associate to it. If the time expires without association of the recipient DEV, connection is considered as failed. If the connection succeeds, the initiator transfers a 1 MByte data file. Data are transmitted through 48-bytes packets at 22 Mbit/s. If no retransmission occurs, file transmission takes approximately 0.5s. The duration between two successive drawings follows an exponential distribution with a parameter being in the same range than one file transfer duration i.e. 0.5s. That aims at loading quite heavily the channel: load is half the capacity. The subset of functions of IEEE802.15.3 standard implemented in the simulation is listed below. As far as the physical layer is concerned, DEVs can use up to two channels. DEVs transmit at the base data rate of 22 Mbit/s. The path loss model used is the one defined in IEEE802.15.2 Draft Recommended Practice [5] for indoor environment. The following features are also managed: scan process, piconet establishment and stop process, association and disassociation process, allocation and channel release mechanisms and PNC handover mechanism. The scan process is not exactly implemented as specified in the IEEE802.15.3 standard. Only one piconet description per channel is collected. Note that the standard proposes to collect the piconet information description for all piconets that can be found in a channel. Concerning the management of channel time allocations, time is fairly shared by the PNC between all the transmissions set up in the piconet at any time. A retransmission mechanism similar to the delayed acknowledgment mode is also implemented.

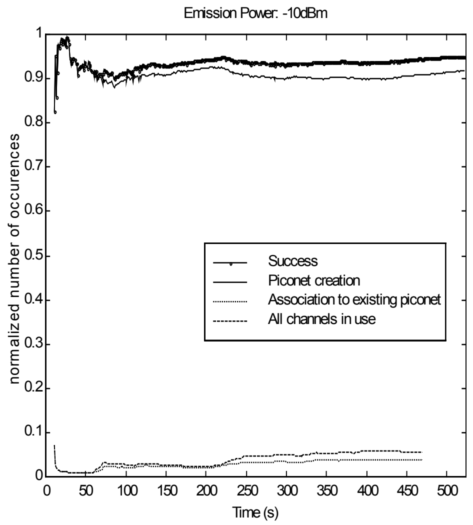

Figure 7. Simulation Results for Emission Power of -10 dBm

Simulations have been performed using different emission power levels: -10 dBm, 0 dBm, and +8 dBm. According to the path loss model, -10 dBm corresponds to the minimum power level that allows a 10-meter transmission with respect to the error rate criterion defined in the standard. The +8 dBm value corresponds to the highest emission power allowed by the standard. For each power levels selected, 1000 drawings of couple are performed. Simulations with different seeds have been performed and show that 1000 drawings are sufficient to get representative results. Simulation results for emission powers of -10 dBm, 0 dBm, and +8 dBm are shown in Figure 7, Figure 8 and Figure 9.

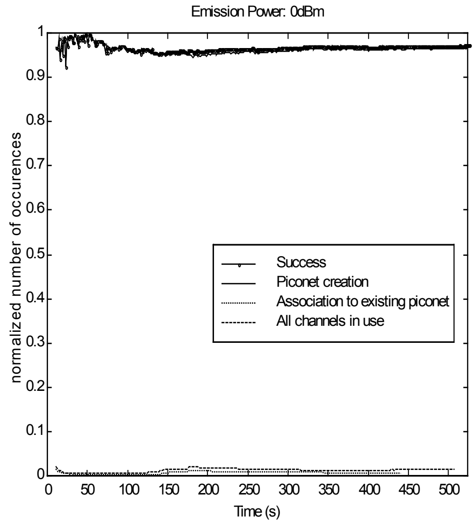

Figure 8. Simulation Results for Emission Power of 0 dBm

The normalized number of occurrences is the number of occurrences of the considered event divided by the total number of requests that have been performed at the measurement time. The curve *Success* (solid line and circles, always the top curve) refers to requests leading to a correct transfer, i.e. the transfer was possible between the two devices. *Piconet creation* (solid line, always the second top curve) and *Association to existing piconet* (dashed line, always the bottom curve) show respectively that the initiator device has become PNC and has created a new piconet or that it has associated to an existing one. Otherwise, the *All channels in use* (dash-dot line, always the third top curve) curve indicates when an initiator device has face all channels already busy.

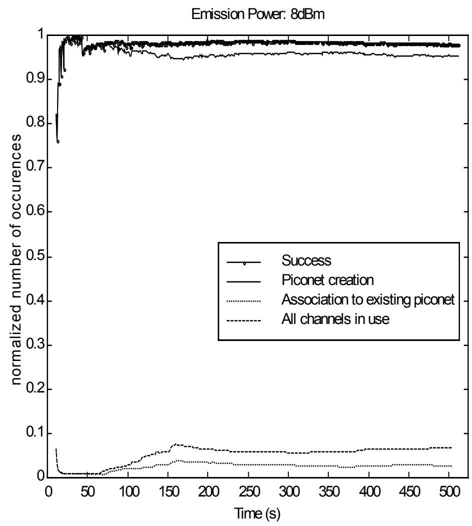

Figure 9. Simulation Results for Emission Power of +8 dBm

First of all, one observes that whatever the emission power is, the probability the data exchange succeeds is high. It varies in the 95%-100% range. In this range, for each emission power considered, one notes two phases: a preliminary dynamic phase followed by a stationary phase. The stationary phase starts in all cases when the curve *All channels in use* reaches its stationary phase. The stationary phase of the *All channels in use* curve is reached more quickly at an emission power of +8 dBm (about 150s) than at an emission power of 0 dBm (about 170s) or at an emission power of -10 dBm (about 250s). The time-lag between the start of the stationary phase in the *All channels in use* curves can be explained by the fact that for a finite area, higher the emission power is less the number of possible topologic configurations is. Before the stationary phase, whatever the considered curve is, connection success is almost exclusively due to piconet creations because in the drawing area and at the drawing time, all channels are not yet in use.

Now, let us discuss the level of the *All channel in use* on the stationary phase. For an emission power of -10 dBm, more piconets can be formed in the defined area at a given time. But, with decreased power, retransmissions are more frequent, channels are longer occupied and hence the *All channels in use* plots are higher for -10 dBm than for 0 dBm. For an emission power of +8 dBm, a small number of piconets is necessary to cover the entire space and then quickly all channels are occupied and the probability to find all the channels busy is high. Hence, *All channels in use* plots are higher for +8 dBm than for 0 dBm. In addition, when multiple transmissions are set up in the same piconet, the channel time is equally shared between all transmissions. When an association occurs, the time needed for data transmission by the whole connections already set in the piconet is increased (in comparison with a single transmission in a piconet) as well as the transmission time for a new connection. Hence, the probability to find all channels in use is again increased. The result for success due to piconet creation is higher for 0 dBm than for +8 dBm because there are more available channels in 0 dBm than in +8 dBm. For 0 dBm there are almost no associations and piconets are small enough to not cover the entire area and saturate all the channels and there is almost no retransmissions. For an emission power of -10 dBm, there are lots of piconets in the area and hence when a device performs a scan as defined in the simulation, it obtains only a partial view of the channel. The view is all the more partial since there are more established piconets in the same channel. This is one of the explanations for the results. For an emission power of +8 dBm it is the opposite. Small numbers of piconets are created and hence the probability to not detect the good piconet for a recipient is low.

Some failures are caused by the fact that only one piconet description is kept during the scan process for each channel. In the standard, all the detected piconets on a channel are signaled. Another failure reason is that the choice of the piconet with the beacon with higher SNR does not always lead to the best choice (see Figure 10) This failure is not directly linked with emission power (induced effect). It's a side effect: for a limited area, if emission power decreases, the number of instantaneous piconets increases and the side effect is more important. It gives us a first explanation on the decreasing efficiency of our algorithm with decreasing power. Another failed reason is directly linked with emission power. With less emission power, DEVs located in the limit of the coverage space suffer difficulties to correctly decode the beacon in case of nearer interfering sources. DEVs are unable to join the piconet and hence the connection fails.

By the introduction of the information element in the beacon, the first issue developed in section III is solved. Association with the beacon with best SNR allows initiator DEV to partially solve second issue developed in section III. The last issue exposed in section III is not solved by the current algorithm proposal. To increase the efficiency of current algorithms an improvement may be to collect all the piconet information description that can be found in a channel as specified by the standard. Introduction of more complex mechanisms like child piconet or proactive PNC handover strategies should also be considered.

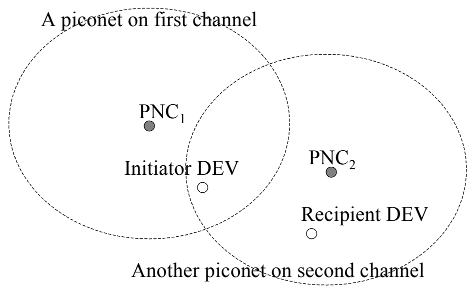

Figure 10. Bad Choice Based on Higher SNR Topology Issue

VI. Conclusion and Further Works

The algorithm proposal for ad-hoc piconet topology initialization is efficient in the whole emission power range defined by the IEEE802.15.3 standard for High Rate WPAN. It leads to a connection success the probability higher than 95%. The current proposal uses very simple mechanisms. The efficiency may be still increased using more complex features defined in the IEEE802.15.3 standard like child piconet and PNC handover. Interests and benefits of such mechanisms will be investigated in future works.

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