Multi-hop Mesh Networking for UWB-based 802.15.3 Coverage Extension

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Abstract

Because of the short-range characteristics of UWB or 802.15.3 networks (around 10 m), it is highly desirable to have a range extension technology for future wireless personal area networks (WPANs). In the 802.15.3 standard, coverage extension is achieved by creating child or neighbor piconets from a parent piconet. One of the main disadvantages of this approach is that it does not make use of the multi-channel capability provided by the underlying physical layer (e.g. multi-band OFDM) as both the dependent and parent piconets operate on the same channel. As a result the capacity of the wireless medium is not fully utilized and the service quality of high rate A/V applications will suffer. This paper first describes a device association scheme to avoid unreachable communication pairs in network initialization. It then proposes a mesh network architecture and a simple, low-cost method for establishing communications across multiple piconets via multi-hop connections. It can be used to extend network coverage through connecting piconets on multiple channels.

1. Introduction

The IEEE 802.15.3 protocol is the chosen standard for high rate Wireless Personal Area Networks (WPANs) [1]. In particular, with the advancement of the Ultra-WideBand (UWB) technology 802.15.3 has been extensively studied as a promising MAC protocol for future UWB networks.

One of the UWB proposals considered in the IEEE 802.15.3a task group is based on the concept of Multi-band Orthogonal Frequency Division Multiplexing (Multi-band OFDM). Multi-band OFDM is a transmission technology where the available spectrum (3.1 - 10.6 GHz) is divided into 14 bands, with each having a bandwidth of 528 MHz. These bands are further organized into five band groups to enable multiple modes of operation for multi-band OFDM devices. Information is transmitted on each band using OFDM modulation. The information bits are interleaved across the bands within a band group to provide robustness against interference. Channelization in multi-band OFDM is achieved by using different time-frequency codes, each of which is a repetition of an ordered group of channel indices [2]. As a result 18 logical channels are provided.

An 802.15.3 network is formed based on the concept of a piconet (shown in Figure 1) [1]. An 802.15.3 piconet consists of several components. The basic component is the DEV (device). One DEV is required to assume the role of the piconet coordinator (PNC) of the piconet. The PNC provides the basic timing for the piconet with the beacon. Additionally, the PNC manages the quality of service (QoS) requirements, power save modes and access control to the piconet. Devices in a piconet can communicate on a peer-to-peer basis.

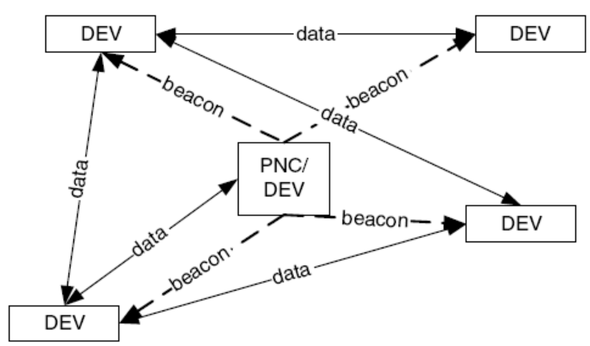

Figure 1: An 802.15.3 piconet

Time of channel access in 802.15.3 networks is governed by so-called superframes. A superframe consists of three parts: a beacon, a contention access period (CAP), and a channel time allocation period (CTAP) (as shown in Figure 2) [1]. The beacon is used to set the timing allocations and to communicate management information for the piconet. The contention access period is used to communicate commands and/or asynchronous data if it is present in the superframe. During the CAP the devices access the channel in a distributed fashion using CSMA/CA and a backoff procedure. The channel time allocation period is composed of channel time allocations

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(CTAs), including management CTAs (MCTAs). CTAs are used for commands, isochronous streams and asynchronous data connections. The CTAP uses a standard TDMA protocol where the DEVs have specified time windows that have guaranteed start time and duration. All the CTAs for the current superframe are broadcast in the beacon.

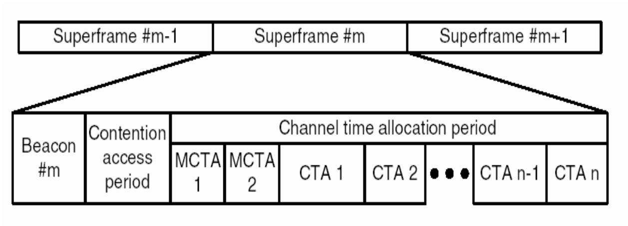

Figure 2: An 802.15.3 superframe

The 802.15.3 standard allows a DEV to request the formation of a subsidiary piconet. In this case, the original piconet is referred to as the parent piconet. The subsidiary piconet is referred to as either a child or neighbor piconet, depending on the method the DEV used to associate with the parent PNC. Child and neighbor piconets are also referred to as dependent piconets since they rely on the parent PNC to allocate channel times for their operation.

Because of the short-range characteristics of UWB or 802.15.3 networks (around 10 m), it is highly desirable to have a range extension technology for future WPANs. In the standard [1], coverage extension is achieved by creating child or neighbor piconets from a parent piconet. One of the main disadvantages of this approach is that it does not make use of the multi-channel capability provided by the underlying physical layer (e.g. multi-band OFDM) as both the dependent and parent piconets operate on the same channel. As a result the capacity of the wireless medium is not fully utilized and therefore it is not an optimal solution for provisioning high-quality service for high rate A/V applications.

This paper proposes a mesh network architecture and a simple, low-cost method for communications across multiple piconets via multi-hop connections. It can be used to extend network coverage through connecting piconets on multiple channels. The paper also describes a method for device association with a piconet to avoid unreachable communication pairs.

The rest of the paper is organized as follows. Section 2 briefly reviews previous work. Section 3 describes in detail the proposed network architecture and route establishment protocol. Section 4 discusses its additional features and advantages. Conclusions and future work are presented in Section 5.

2. Related work

The exact method of establishing connections across multiple piconets on multiple channels via possible multi-hop links is not specified in the current standard. There are not many works in the literature that address this issue either. In the past multi-hop communications in WPANs have mainly been studied in the context of Bluetooth scatternets, e.g. [3]. A multi-channel scheduling algorithm in UWB networks is proposed in [2]. It is based on an abstract network model and focuses on scheduling connection requests in a collision-free manner. It does not specify how devices in neighboring piconets communicate to each other. Recently there are also a number of papers on using multiple channels of 802.11 for capacity improvement in mesh networks (e.g. [4] [5]), but they are not directly applicable to 802.15.3 WPAN networks due to their different protocol architectures.

3. Multi-hop multi-channel 802.15.3 mesh networks

3.1. Device association

In the standard, on initialization a DEV (a potential PNC) scans the available channels and chooses a free channel. After listening to the selected channel for a period of time to make sure the channel is free, it is permitted to start a new piconet on this new channel. Alternatively a DEV can join an existing piconet. Before we start discussing the range extension problem, we recognize that it is possible that two devices that are within transmission range of each other may not be able to establish communication because they belong to two different piconets. Therefore care should be taken in the first place in network initialization to avoid unreachable communication pairs due to their association with different piconets.

Devices that are most likely to communicate to each other should be clustered into the same piconet (and same channel) if possible upon network initialization. For example, when UWB is used as a cable-replacement or wireless USB technology for an application of transmitting HDTV signals between a DVD player and a television set, they should be in the same piconet. One way to achieve this is to introduce a list of intended (potential) communication partners in the device association process. When a DEV joins an existing piconet by sending out an Association Request command to the PNC [1], it includes an Information Element (IE) that indicates a list of potential partners. Then the PNC checks its resources and sends back an Association Response command including an IE that indicates the intended communication partners that are already in the piconet. Upon receiving the Association Response command the DEV sends a *second* Association Request command to complete the association process if it is

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satisfied that its intended partner is within the same piconet.

As an example, Figure 3 shows that there are two piconets in the vicinity of a DVD player that is trying to join one of them. From the Association Response it receives, the DVD player learns that the TV is actually in piconet 1 so it has decided to join piconet 1.

Although the above method can improve the chance of communication partners being associated with the same piconet, there still exists the problem of inter-piconet communications between devices belonging to different piconets due to various reasons, e.g. distance or administration. We address this issue in the following subsection.

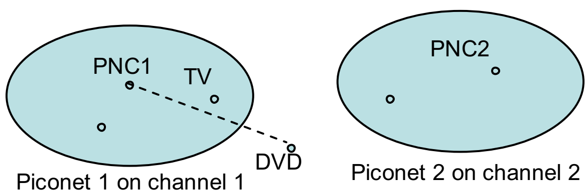

Figure 3: Piconet association

3.2. Inter-piconet communications

Devices within the same piconet can communicate to each other as per the 802.15.3 standard. Since an 802.15.3 piconet supports peer-to-peer communications between DEVs, peer discovery is crucial to its operation. If the necessary peer information is not available, a DEV needs to execute a peer discovery procedure before any actual data transmission. Each DEV in the 802.15.3 piconet may use the PNC Information Request command to obtain information about other DEVs in the piconet from the PNC. A Probe Request message may also be sent by a DEV directly to another DEV to obtain other information required for peer-to-peer communication. In addition, all DEVs in the piconet are able to use the Channel Status Request and Channel Status Response commands to gather information about the quality of links between DEVs [6]. All these commands are exchanged in the contention access period of superframes.

In contrast to the above intra-piconet scenario, this paper is mainly concerned with communications across a larger area which can only be covered by more than one piconets, i.e. inter-piconet communications. As shown in Figure 4, there are two independent piconets on two different channels (channel 1 and channel 2 respectively), forming a mesh network. The two piconets can be overlapping. In each piconet, there is a PNC. In a home network scenario, a device with unrestricted power supply and high processing capability (e.g. a media centre) can be chosen as the PNC. Location information can also be taken into account. The two PNCs can be connected wirelessly[1] or via a wired link. Furthermore, with gateway functionality, PNCs can be connected to the Internet. In this way PNCs form a mesh of infrastructure or backbone for devices that connect to them. Without loss of generality, in the following discussions we assume that the wireless links between PNCs are based on 802.15.3 and they learn each other's existence by regularly exchanging HELLO messages which include their own channel information. The HELLO messages are sent during the contention access period and the frequency of sending HELLO should be small compared to normal piconet beacon intervals to reduce overhead. In our example of Figure 4 PNC1 sends out HELLO messages on channel 2 so that PNC2 is aware of the fact that there is a piconet 1 nearby on channel 1, and vice versa. Hence a PNC is not only responsible for coordinating communications within its own piconet, but also establishes communication links with other piconets.

For the sake of simplicity there are only two piconets shown here: there could be more piconets and the discussion can be easily extended. We further assume that devices are equipped with a single transceiver that is able to switch channels. In other words a device can only transmit or receive on one channel at a time. Note that devices with multiple network interface cards (NICs) are more expensive and the resulting routing and channel assignment problem is much simpler. In the following we describe two ways to establish connections across multiple piconets.

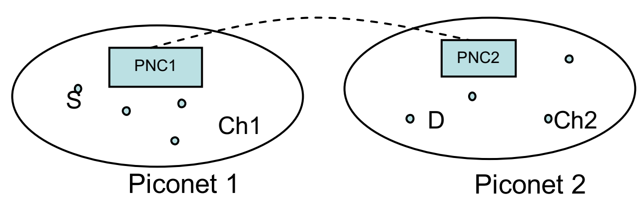

Figure 4: An 802.15.3 mesh network

3.2.1. Method 1

As an example for the range extension problem, assume that device S in piconet 1 intends to communicate to device D far enough away that is in another piconet, piconet 2. When MAC layer peer discovery within a piconet fails (because S and D are in different piconets), normally the MAC protocol will notify the network layer to initiate a route discovery process by flooding Route Request (RREQ) packets, as in the AODV routing

[1] Theoretically the wireless link between PNCs can be built using various types of radio technologies, e.g. 802.11. However, the issue of co-existence of different wireless MACs is outside the scope of this paper.

protocol [7]. Since all RREQs are broadcast in the contention access period, it adds considerable overhead and may result in many collisions. Furthermore, the original AODV protocol only works for single channel networks. Note that in an 802.15.3 network there is a central control entity, i.e. the PNC, which should be utilized in the route discovery process. In our protocol, the source S *unicasts* a RREQ to PNC1 trying to discover D. The format of the RREQ could be the same as that specified in the AODV standard [7]. Upon receiving this RREQ, PNC1 multicasts it to all the neighboring PNCs on all channels, one at a time. Basically, PNC1 first sends the RREQ to PNC2 on channel 2 and waits for some time to collect any response and then moves on to the next channel (PNC). Eventually after going through all the channels, PNC1 returns to the original channel, channel 1.

Upon receiving the RREQ from PNC1, PNC2 knows that D is within its piconet and forwards the RREQ to D. Similar to the route discovery procedure in AODV, D replies with a Route Reply (RREP) all the way back to source S via PNC2 and PNC1. A channel time request (CTRq) is incorporated in the RREP. When PNC2 receives this RREP, it will build a beacon and allocate channel time accordingly in piconet 2 for this connection. Once the source S receives the RREP, it will send a channel time request to PNC1 and PNC1 will allocate a CTA. By then the route S-PNC1-PNC2-D has been established and S can start transmitting. We will elaborate more on channel time allocation later in this paper.

As in AODV, route information (IP address, hop-count, sequence number, etc.) is maintained by each PNC in its route table. In this way when another node (other than S) in piconet 1 intends to communicate to D in piconet 2, PNC1 already has a *current* route and can inform PNC2 (for channel time allocation) immediately without multicasting a RREQ through all the channels (PNCs) to discover the route.

For a connection across piconets on multiple channels (channels 1 and 2 in this example), there exists the problem of channel assignment [4] [8]. There are two approaches for channel assignment of this connection. The first approach is to assign channels to nodes independent of traffic flows. In this approach, nodes send packets by switching to the channel of the receiver, whenever they have packets to transmit. In this case, after the route is established, S sends packets to PNC1 on channel 1, and then PNC1 switches to channel 2 to transmit to PNC2, etc. So here PNC1 is the *switching* node. The benefit of this approach is that route establishment is decoupled with channel assignment. However, the downside is that there is a channel switching delay which is about 9 ns for multi-band OFDM [2]. This means per-packet channel switching can add considerable overhead (delay) to the protocol.

The second approach in channel assignment is to assign channels to connections instead of nodes. This means that whenever a route is established, all nodes in the route are assigned with a common channel. In this paper we adopt a rather simple approach. When the destination receives the RREQ, it will choose the channel that it is currently on for the connection and sends back a RREP. In our example, D selects channel 2 for the connection and includes this information in the RREP (by adding a “channel” field) to inform all the nodes on the route. Upon receiving this RREP, the source S (and PNC1) in piconet 1 needs to switch to channel 2 before starting its transmission. After the connection is finished, S switches back to its original channel. Note that if S is also involved with intra-piconet communications with other DEVs on channel 1, it has to switch between two channels, i.e. it becomes a switching node.

Because a switching node switches channels from time to time, another node may fail to send packets to the switching node if the switching node is listening on another channel. So other nodes in the piconet must know whether the switching node is still on the same channel. To this end, a switching node can use SWITCH messages (which include a “channel” field) to inform others of its channel status [4]. Suppose S switches its channel from 1 to 2. Before switching channels, S sends a SWITCH message on channel 1, indicating that it is switching to channel 2. When S returns to channel 1, it broadcasts a SWITCH message indicating it is back to channel 1. Obviously, more intelligent algorithms are also possible that take into account channel conditions and traffic load in choosing channels at the destination.

Figure 5 presents an example of the RREP message. In addition to those fields present in standard AODV it also includes a channel field and a CTRq field. Figure 6 shows a flowchart of the establishment of multi-hop route in an 802.15.3 mesh network according to Method 1.

Type	Hop Count
Destination IP Address	Destination Sequence Number
Source IP Address	Lifetime
Channel	**CTRq**

Figure 5: RREP message

3.2.2. Method 2

The main difference between this method and the previous one is that here the PNC maintains a neighbor piconet table. PNCs exchange channel information and the list of devices within their piconets to form a *neighbor piconet table (NPT)*. This can be done using HELLO messages sent on all channels in a round-robin fashion. PNCs exchange a complete copy of their NPT tables upon initialization. Then, like link-state protocols, updates are multicast only when a change (e.g. device arriving or leaving) has occurred. When a PNC receives the HELLO message, it updates its neighbor piconet table according to the information given in the message. When the number of piconets or the number of devices is large, this NPT can be quite big.

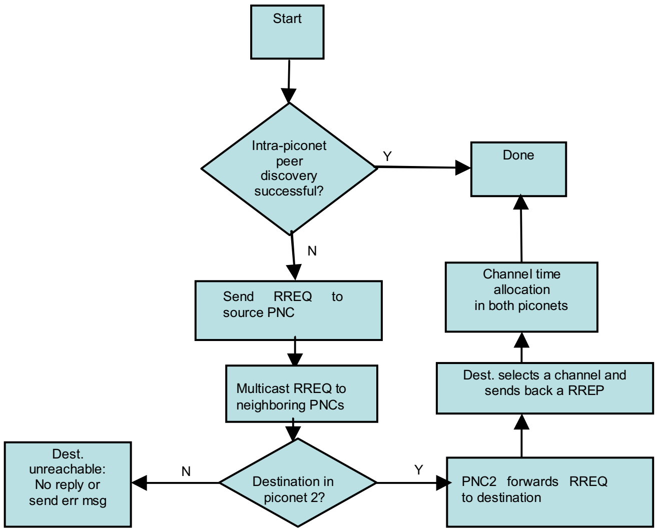

Figure 6: Flowchart for route discovery

For route discovery, the source S unicasts a RREQ to PNC1 trying to discover D. Upon receiving this RREQ, PNC1 looks up its NPT table and learns that device D is actually in piconet 2. So PNC1 informs PNC2 straightaway. Upon receiving the RREQ from PNC1, PNC2 knows that there is an incoming connection destined for one of the devices in its piconet. It will build a beacon and allocate channel time accordingly in piconet 2 for this connection. In the meantime PNC2 will send a response to PNC1 indicating that channel time has been allocated for this connection. PNC1 will then inform S and allocate channel time in piconet 1.

Compared to Method 2, although Method 1 involves more communication overhead during the route discovery phase (PNC1 needs to contact all the other PNCs), it is more scalable because it does not need to maintain tables for devices in neighbor piconets at each PNC.

3.2.3. Channel time allocation

An important issue related to multi-hop multi-channel connections is channel time allocation. The exact method for CTA is not specified in the standard. Channel time allocation across multiple hops without coordination is inefficient. For example, when the link in piconet 2 fails, PNC1 is unaware of this and could continue allocating channel times for other hops of the flow [6]. In this respect, route maintenance procedures such as those in AODV [7] are useful. When a route breaks, a Route Error (RERR) message is sent to the upstream nodes and traffic needs to be re-routed. PNCs then terminate (release) or re-allocate channel times accordingly. Further, a *unique* flow ID for the entire flow over multiple hops can be defined. In the original 802.15.3 standard, there is a stream index defined for use only in a single piconet. The new flow ID replaces the old stream index in channel time allocation so that the flow can be identified over multiple piconets.

Back to our example of Figure 4, in piconet 2 during the route discovery process when PNC2 receives the RREP from D, it assigns two CTAs on channel 2: one CTA for the link between PNC1 and itself, and another CTA for the link between itself and the destination D. Depending on whether a common channel (e.g. channel 2) is chosen for the entire flow or the flow traverses multiple hops on different channels, in piconet 1 PNC1 is responsible for CTA assignment for the link between the source S and itself either on channel 2 or channel 1.

4. Discussion

This paper has described a generic, mesh network architecture for 802.15.3 home networks. It is flexible in that various routing and channel assignment techniques can be applied here according to the trade-off between performance improvement and implementation complexity. For example, traffic load can be taken into account in piconet formation to achieve load balancing and better QoS [4]. When piconet 1 in Figure 4 has a much lighter load than piconet 2, a node in piconet 2 can switch to channel 1 and associate with piconet 1. In general, however, optimal multi-hop piconet (or scatternet in Bluetooth terms) formation according to some optimization objectives is a very complex problem that is subject to further study.

QoS can also be combined with route discovery. For instance, bandwidth requirement can be incorporated in the RREQ packets and PNCs can perform admission control for flows based on this QoS information and their available resources (e.g. [9]). For delay-sensitive multimedia traffic such as MPEG-4 encoded video, more sophisticated channel time allocation approaches are available, e.g. traffic prediction-based channel time allocation [10].

Note that the recent 802.11e standard is very similar to 802.15.3 (except that 802.11e has service differentiation through traffic categories). So the protocol described here can also be applied to 802.11e with little modification. In that case, the hybrid coordinator (HC) in 802.11e takes on a similar role to the PNC in 802.15.3 networks, while the hybrid coordination function (HCF) of 802.11e also defines two phases of operation: a contention period (CP) and a contention-free period (CFP).

5. Conclusion

UWB-based 802.15.3 networks have the potential to support high data rate applications, but have short range transmission limitations. Child and neighbor piconets are not flexible and do not fully utilize the channel capacity. On the other hand, range extension in multi-channel 802.15.3 networks is not covered in the current standard. The proposed scheme makes use of the PNC of a piconet as a "switching hub" and combines functionalities of MAC layer piconet management and network layer route discovery. Involving PNCs in multi-hop route establishment facilitates easier resource management as PNCs are responsible for channel time allocation in 802.15.3 networks. The protocol also avoids network-wide flooding which would add extra delay and overhead. As a result, the proposed method can be used as a simple, low-cost solution to extending coverage of 802.15.3 networks.

We are currently in the process of developing a multi-channel 802.15.3 network simulator to test the performance of the proposed protocol. Performance metrics of interest are connection establishment success ratio, route discovery delay and protocol overhead (e.g. number of exchanged messages, especially channel switching messages). The impacts of control packet collisions and intra-piconet background traffic on multi-hop connection establishment are to be investigated. Incorporating a more accurate physical layer UWB model (e.g. multi-band OFDM) into the simulator is also part of our future work. Another important aspect that needs further investigation is the heterogeneity of networks, e.g. how to establish inter-piconet communications between piconets based on different physical and MAC layer technologies.

Acknowledgements

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