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A survey on Bluetooth multi-hop networks

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ABSTRACT

Bluetooth was firstly announced in 1998. Originally designed as cable replacement connecting devices in a point-to-point fashion its high penetration arouses interest in its ad-hoc networking potential. This ad-hoc networking potential of Bluetooth is advertised for years - but until recently no actual products were available and less than a handful of real Bluetooth multi-hop network deployments were reported. The turnaround was triggered by the release of the Bluetooth Low Energy Mesh Profile which is unquestionable a great achievement but not well suited for all use cases of multi-hop networks. This paper surveys the tremendous work done on Bluetooth multi-hop networks during the last 20 years. All aspects are discussed with demands for a real world Bluetooth multi-hop operation in mind. Relationships and side effects of different topics for a real world implementation are explained. This unique focus distinguishes this survey from existing ones. Furthermore, to the best of the authors' knowledge this is the first survey consolidating the work on Bluetooth multi-hop networks for classic Bluetooth technology as well as for Bluetooth Low Energy. Another individual characteristic of this survey is a synopsis of real world Bluetooth multi-hop network deployment efforts. In fact, there are only four reports of a successful establishment of a Bluetooth multi-hop network with more than 30 nodes and only one of them was integrated in a real world application - namely a photovoltaic power plant.

1. Introduction

Since Bluetooth Core Specification version 4.0 that was adopted in June 2010 two versions of Bluetooth technology have existed side by side: Classic Bluetooth and Bluetooth Low Energy (BLE). Both technologies define concepts for device discovery, connection establishment and connection management. But the features and use cases differ resulting in distinct design decisions: Devices using BLE should require less power, should be less complex and thus, should be less expensive than classic Bluetooth ones. Furthermore, applications built on BLE should call for lower data rates and duty cycles than the ones using classic Bluetooth [1].

The fundamental key characteristic of Bluetooth before Core Specification version 4.0 in 2010 was its connection-orientation: data transmission between two Bluetooth devices was possible only after establishing a connection. With the release of BLE as second independent Bluetooth technology in 2010 and the definition of two BLE key features with Bluetooth Core Specification version 4.1 in 2013 a paradigm shift was triggered that lead to the release of the BLE Mesh Profile in 2017. The BLE Mesh Profile enables the operation of connectionless Bluetooth multi-hop networks.

The basic connected Bluetooth topology is a piconet consisting of a master and a set of slaves. The devices form a star topology with the master coordinating the whole communication by polling its slaves. The Bluetooth specification abstractly describes the interconnection of several piconets to larger networks called scatternets. Scatternets are composed of interconnected piconets linked through bridge devices participating in more than one piconet using time division multiplex. In the following the term “scatternet” refers to connected Bluetooth multi-hop networks as defined by the Bluetooth Core Specification. The implementation of a Bluetooth scatternet explicitly needs to address the topics scatternet formation and maintenance, inter-piconet scheduling and multi-hop packet forwarding [2–5]. Bluetooth scatternets are a subset of Bluetooth multi-hop networks. Connectionless Bluetooth multi-hop networks rely on the flooding concept by using a shared broadcast channel. Thus, the topics scatternet formation and maintenance and inter-piconet scheduling are not relevant. The BLE Mesh Profile was made publicly available more than three years after the specification of BLE key features to support BLE multi-hop networks. As a consequence, proposals for the realization of connected and con-

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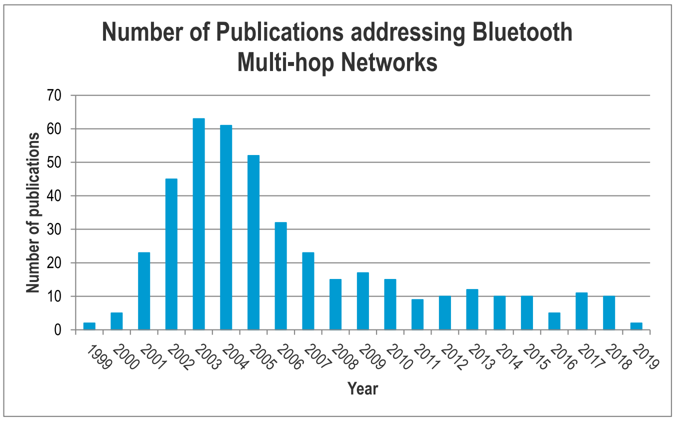

Fig. 1. Number of publications addressing Bluetooth multi-hop networks per year. The whole population comprises more than 400 publications.

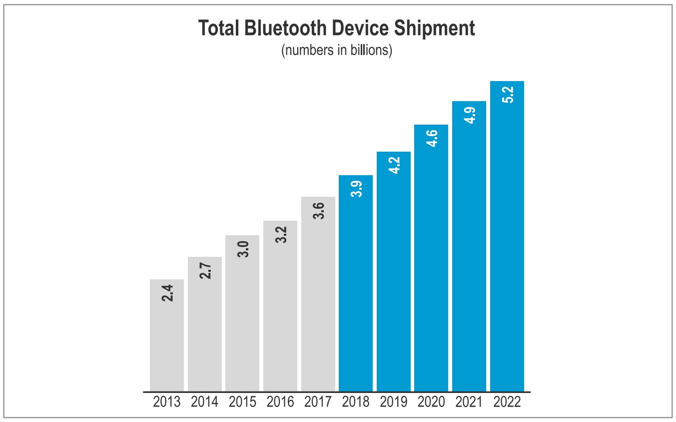

Fig. 2. Total number of shipped devices equipped with a Bluetooth interface between 2013 and 2022 (values represented by blue bars are forecasted) [14]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

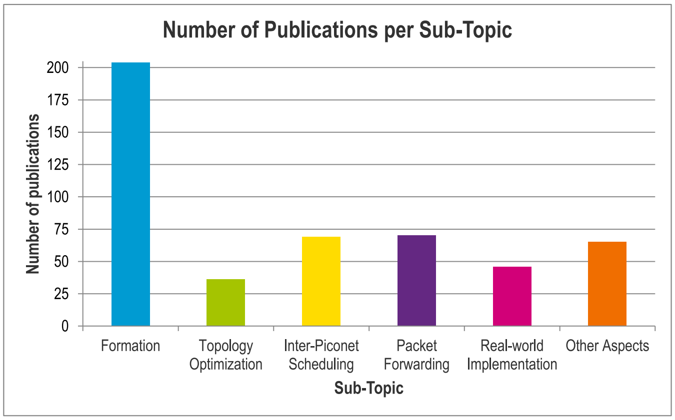

Fig. 3. Number of publications addressing different sub-topics of Bluetooth multi-hop networks. One publication can address more than one sub-topic.

nectionless BLE multi-hop networks were published in the meantime. According to Darroudi and Gomez different companies developed proprietary BLE mesh network solutions to explore the BLE mesh network's market potential [6].

Numerous publications highlight the enormous potential of Bluetooth multi-hop networks, e.g. [6–11]. Lee et al. argue that BLE outperforms IEEE 802.14.5 in case of data rate, power consumption and in connected networks in terms of interference mitigation through Frequency Hopping Spread Spectrum (FHSS) and the time division multiplex Medium Access Control (MAC) protocol [12]. Throughout the last 20 years (1999–2019) a plethora of publications addressed the subject of Bluetooth multi-hop networks. But there are only a few reports concerning real world Bluetooth multi-hop network implementations given measured values of important network metrics like throughput, communication delay, reliability etc. It is first mentioned in 2014 that the spotlight of research is pointed on realistic scenarios [13]. Furthermore, there is no comprehensive up-to-date survey drawing the big picture of Bluetooth multi-hop networks research and implementation efforts. The last survey addressing many aspects of Bluetooth scatternets was published in 2004 [2] but it neither consider real world implementations nor BLE solutions. And a survey on BLE multi-hop networks was published in 2017 [6] but it was published right before the BLE Mesh Profile was released. Consequently, it is not known which pieces of the puzzle are missing to be able to exploit the promising potential of Bluetooth multi-hop networks for a wide range of applications: building big Bluetooth ad-hoc networks composed by tens to hundreds of nodes.

Fig. 1 visualizes the number of publications on the subject of Bluetooth multi-hop networks per year. The whole population includes more than 400 publications. The collection does not claim to consider all available publications on Bluetooth multi-hop networks but it is large enough to draw representative conclusions. A peak of publications is visible from 2002 to 2006. But there are Bluetooth multi-hop networks related publications until today and an end of research interest is not seen [15] - because of the promising potential of Bluetooth ad-hoc networking driven by the availability of Bluetooth capabilities in many devices [16]. According to Jedda et al. [16] 95% of today's smartphones incorporate a Bluetooth interface. Furthermore, there are a plenty more devices like smart watches, heart-rate monitors, blood-glucose meters, window and door security sensors, car key fobs etc. equipped with Bluetooth [16]. The Bluetooth Special Interest Group (SIG) gives a number of nearly 4 billions Bluetooth devices shipped in 2018 alone as forecast in their 2018 market update [14] as indicated by Fig. 2. And ABI Research estimated in 2013 that there will be around 10 billions devices equipped with a Bluetooth interface in 2018 [17]. Based on Fig. 2 this forecast was even exceeded: The sum of shipped Bluetooth devices from 2013 to 2017 alone is nearly 15 billions devices [14].

In addition to consider the number of publications per year the detailed sub-topics of the publications were analyzed and illustrated by Fig. 3. Of course, it is possible that one publication addresses more than one sub-topic. The remainder of this survey paper is oriented towards the sub-topic analysis. Section 2 gives a short introduction to Bluetooth's technology basics followed by Section 3 that introduces the basic concepts of the BLE Mesh Profile. Nearly half of all publications make Bluetooth scatternet formation protocols the subject of discussion. Scatternet's topology maintenance and optimization approaches are closely related to scatternet formation procedures and thus, are covered in Section 5. Inter-piconet scheduling and packet forwarding in Bluetooth multi-hop networks go head to head concerning the number of related publications. Inter-piconet scheduling mechanisms are addressed in Section 6 and packet forwarding in Bluetooth multi-hop networks is reviewed in Section 7. Most of the publications (85%) spanning the entire period from 1999 to today (05/2019) are based on simulations or analytical results or they are described conceptually solely. Several publications highlight the need for real world implementations and investigations [15,18,19]. Therefore, real implementations are looked at in detail in Section 8. All other top-

Table 1
Comparison of classic bluetooth and bluetooth low energy.

Property	Classic Bluetooth	Bluetooth Low Energy
Optimized for	Continuous data streaming [22]	Short burst data transmission [22]
Frequency Range	2400…2483.5 MHz	
Channel Allocation	79 channels f = 2402 + k MHz (k=0… 78)	40 channels f = 2402 + k*2 MHz (k=0… 39)
Modulation	GFSK (BR) $\pi/4$ DQPSK (EDR), 8 DPSK (EDR)	GFSK
Data Rate	up to 723.2 kbps (BR) up to 2178.1 kbps (EDR)	up to 236.7 kbps [23], 221.7 kbps [24]
TDMA Units	Fix sized (time) slots	Variable sized events
FHSS	Per packet	Per event
Connectionless Communication	✗	✓
Device Roles	Inquiring device, inquiry scanner, paging device, page scanner, master, slave	Advertiser, scanner, initiator, master, slave
Explicit Low Power Modes/State	✓	✗
Piconet Communication Topology	Star	
Scatternet Support	✓	✓
Slave Role: Number of Connections ≥ 1	✓	✓
Dual Role	✓	✓
Role Switch	✓	✗

ics related to Bluetooth multi-hop networks are summarized in Section 9. A concluding section finishes the paper.

2. Bluetooth basics

Classic Bluetooth as well as BLE use the Frequency Hopping Spread Spectrum (FHSS) technology in the 2.4 GHz unlicensed Industrial, Scientific and Medical (ISM) band [20,21] and share some other characteristics (as indicated by Table 1) but are not interoperable at all [1]. Although the frequency range used is 2400…2485 MHz for both technologies the channel allocation differs: classic Bluetooth uses 79 frequency channels separated by 1 MHz whereas 40 channels separated by 2 MHz are used in BLE [25,26]. As a consequence of the deployment of the FHSS technology devices using either Bluetooth technology have to be synchronized to the same frequency channel at the same time in order to communicate [27,28]. The characteristics of the frequency hopping differ widely. Classic Bluetooth devices change the frequency channel per packet [20] - commonly 1600 times per second or at least 320 times a second (for 5 slots packets) - whereas connected BLE devices switch the frequency channel per Connection Event with a maximum length of 4 s [21].

In classic Bluetooth the device discovery is accomplished by the inquiry and the connection establishment by the page procedure. An inquiring device transmits inquiry packets - called Identification (ID) packets - and listens for inquiry responses - called Frequency Hop Synchronization (FHS) packets [31]. Devices in the neighborhood have to be in inquiry scan state in order to receive ID packets and respond with FHS packets. The ID packet only contains a synchronization word and thus, no information concerning the inquiring device [32]. In contrast, the FHS packet comprises the Bluetooth address of the responding device and some other information [32]. Since Bluetooth Core Specification version 2.1 the Extended Inquiry Response (EIR) is defined. This mechanism can be used to provide miscellaneous information about the responding device during inquiry (maximum 240 bytes) [33]. The inquiry procedure does not establish a connection between devices [31]. This task is done by the page procedure: One device carries out the paging whereas one specified other device responses during the page scan procedure. The paging is targeted at one specified device identified by the Bluetooth address obtained during the inquiry procedure [33,34]. For classic Bluetooth devices it is not possible to exchange any user data without establishing a connection (except for the limited capabilities of the Extended Inquiry Response). The paging device always starts out as master of the connection [34] whereas the device responding a page request becomes the slave. In general, every device is able to accomplish master and slave role and consequently, the roles may be switched once a connection is established [35]. Device discovery and connection establishment concepts are entirely changed in BLE and new terms were required to be introduced. The fundamental terms “master” and “slave” are kept for connected BLE devices. But in contrast to classic Bluetooth devices using BLE are able to stay unconnected and still exchange user data with other BLE devices. These devices are in advertising or scanning state and accordingly, are referred to as “advertisers” or “scanners”. Advertising and scanning procedures are also used to discover other BLE devices in vicinity. A discovering device listens for certain advertising events actively broadcasted by discoverable devices over the advertising broadcast physical channels [33]. Thus, the device discovery procedure of BLE is fundamentally different from the one of classic Bluetooth [36] and due to the use of only three different frequency channels (instead of 32 in classic Bluetooth) considerably less complex. Another term is used to describe the connection establishment procedure in BLE: Scanning devices that receive a packet from a connectable advertiser can initiate a connection request and thus, are referred to as “initiators”. The advertising can be targeted [33]. If the advertiser accepts the connection request the initiator will start out as master and the advertiser will become the slave of that connection [21]. The Bluetooth Core Specification version 4.0 prohibits BLE slaves to have more than one connection at a given time and thus, the slaves cannot be member of more than one piconet. Moreover, Bluetooth Specification version 4.0 does not permit devices to operate in dual role (master/slave) [37] and the role switch for BLE devices is prohibited [21]. The first two constraints are removed with Bluetooth Core Specification version 4.1 [38] whereas the master/slave role switch is still not permitted by the most recent Bluetooth Core Specification version 5.1 [39].

Bluetooth technology is connection-oriented and thus, a master has a dedicated connection to each of its slaves [20,21]. The basic Bluetooth topology is a piconet consisting of a master and a set of slaves. The number of active slaves is limited to seven for classic Bluetooth [40] whereas the BLE specification does not restrict the number of slaves [41]. The communication topology is a star: The master is able to communicate with each of its slaves in a Time Division Duplex (TDD) manner. Slaves are not able to communicate with each other directly but via their master [20,41]. All active devices of a piconet use a shared frequency channel in classic Bluetooth, i.e. all devices synchronously switch the frequency channel according to the unique frequency hopping sequence of that piconet determined by the piconet master [41,42]. Devices of a BLE piconet do not use a shared frequency channel. The master specifies a unique hopping sequence for each point-to-point connection to each of its slaves [42]. The master applies polling to

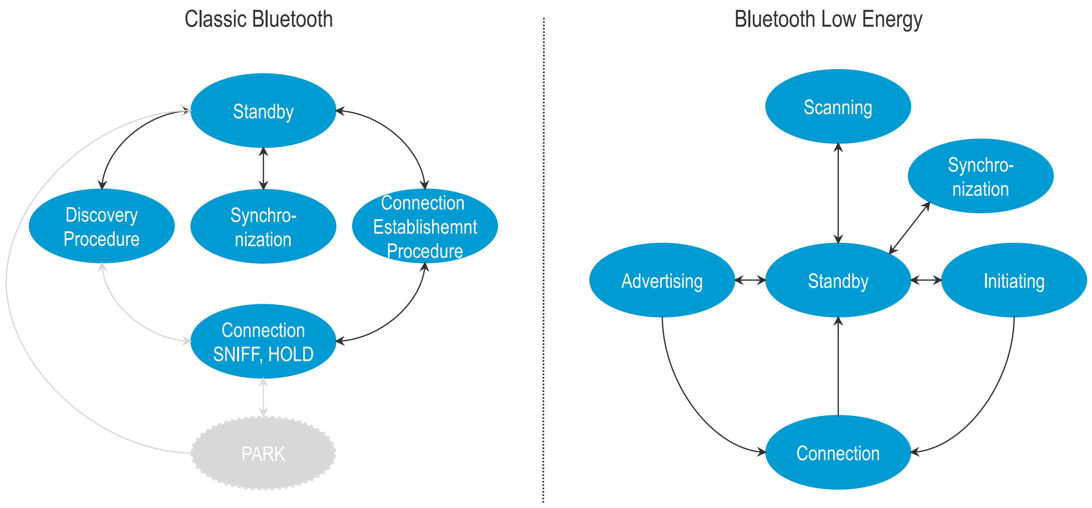

Fig. 4. States of classic Bluetooth devices (left side) and BLE devices (right side). The PARK state of classic Bluetooth was discarded with Bluetooth Core Specification 5.0 and therefore, it is displayed in light gray. The paradigm shift of BLE is clearly visible: The center of operation is the standby state which can be used to save power. In classic Bluetooth the center was built by the connection state accessible through the connection establishment states soley. Figure based on Figure 2.1 of Ref. [29] and Figure 2.1 of Ref. [30].

consecutively communicate with its slaves [21,43] and thus, uses time division multiplex. Polling in the context of classic Bluetooth is also known as intra-piconet scheduling [44]. The time units used by the master to realize the TDMA are called slots [45]. The frequency channel basically is switched 1600 times per second and thus, a time slot is 625 µs of length [35,45]. In BLE the TDMA time units changed: instead of using fixed slots BLE uses events of variable length (7.5 ms…4.0 s) [21,46]. These events are called Connection Events and are regularly spaced for each slave with a Connection Interval interval. Master and slave exchange packets within the Connection Event using one frequency channel [46]. Table 1 juxtaposes the characteristics of classic Bluetooth and BLE.

Classic Bluetooth devices enter the connection state in order to exchange data packets. The connection state has three modes: active, SNIFF and HOLD [43]. In the active mode master and slave actively participate on the channel [43] whereas the SNIFF and HOLD mode can be used to reduce the activity of the slaves [43]. In SNIFF mode a slave can reduce the number of slots it has to listen on the channel and in HOLD mode a slave can get capacity to do other things like scanning, paging, inquiring, or attending another piconet [43]. The PARK state can be used for low power consumption and indicates that a slave does not need to participate on the channel [47]. But the parked slaves still remain synchronized to the channel by periodically waking up [47]. Parking and unparking of slaves can be used by the master to establish connections to more than seven slaves in a piconet. But only seven slaves can be in connection state at a time [47]. The PARK state was conceptually discarded in Bluetooth Core Specification version 5.0 [48]. Fig. 4 presents the device states of both Bluetooth technologies face by face. BLE devices do not need explicit low power modes. Devices will use the Standby state that can be entered from any other state if no data has to be exchanged. Furthermore, it is not necessarily required to enter the connection state in order to communicate. But a connection establishment is needed to participate in a piconet [21,49]. Synchronization state is defined since Bluetooth Core version 4.1 for classic Bluetooth [50] and since Bluetooth Core version 5.1 for BLE [51].

The Bluetooth Core Specification conceptually describes the interconnection of several piconets to larger networks called scatternets [43]. The scatternet concept has been described for classic Bluetooth since Bluetooth Core Specification version 1.0 [52] and for BLE since Core Specification version 4.1 [53]. Interfaces between piconets are Bluetooth nodes that are member of more than one piconet: the bridge nodes. Bridges apply time division multiplex to communicate in different piconets. Two Bluetooth nodes (master and slave) will be only able to communicate directly if they are simultaneously active in the same piconet [3]. A bridge node can be of two types: a master/slave (M/S) bridge is master in its own piconet and slave in other piconet(s) whereas a slave/slave (S/S) bridge is slave in at most two piconets [54]. Each piconet (classic Bluetooth) or each connection of a piconet (BLE) is coordinated by its master: the master determines the timing and the frequency hopping sequence [3,46]. Consequently, bridge nodes have to synchronize to different piconet properties when switching between piconets. Each piconet in a scatternet is autonomous and has especially its individual clock base. Switching of bridges between piconets is controlled by inter-piconet scheduling.

The realization of the Bluetooth functionality is split into two architectural blocks: the Bluetooth controller and the host. The Bluetooth controller typically is the hardware Bluetooth module used whereas the host is built by the main processor of the system. The interface between Bluetooth controller and host is the Host Controller Interface (HCI) specified by the Bluetooth Core specification. The interoperability between Bluetooth devices is provided per service or use case by Bluetooth profiles. A Bluetooth profile defines a set of messages and procedures from the Bluetooth Special Interest Group (SIG) specifications and describes the air interface between two devices supporting the service or use case [55].

3. BLE Mesh Profile

The BLE Mesh Profile is based on a full BLE stack. The mesh concept uses the fundamental wireless communication capabilities of BLE. The BLE mesh network is a topology option for BLE devices. Each device in a BLE mesh network is able to communicate with each other device of that network [56] â provided that the physical topology allows for it [57]. The BLE mesh network was designed to support large-scale multi-hop networks and thus, is ideally suited for automation, sensor networks, asset tracking and any other use case that require the secure communication of ten to thousands devices [58]. The BLE mesh concept can be considered as a paradigm shift extending the established Bluetooth characteristics to fully support multi-hop networks [56].

Devices of a BLE mesh network are called nodes. BLE devices need to be explicitly associated to a BLE mesh network. This procedure is called “provisioning” and consists of several steps. At the end of this procedure a node has a network key that represents the node’s membership to a certain mesh network [56].

A BLE mesh node may consists of several elements, e.g. a LED panel with three spots is a node consisting of three elements. The elements can be in various states represented by state values in BLE mesh networks [56]. An element that exposes a state is a server whereas an element that accesses a state is a client [59]. The entire communication in BLE mesh networks is message-oriented. Messages are used to trigger operations on a state value or on a set of state values. Messages can be roughly classified into three types: GET, SET and STATUS. The GET messages are used to request the value of a given state. STATUS messages are sent in response to the reception of GET messages and SET messages are used to modify the value of a given state [56].

The BLE Mesh Profile defines unicast and two types of group addresses. A unicast address identifies one element and is assigned during the provisioning. Group addresses are multicast addresses that represent one or more elements belonging to one or more BLE mesh nodes [56]. Messages are typically sent to group addresses. The communication model in BLE mesh networks is of type publish/subscribe: A node sending a message publishes this message and other nodes are configured to receive messages sent to defined address(es). The receiving nodes are known as subscribers to at least one address [56].

All nodes of a BLE mesh network are able to send and receive messages. But a node can be configured to optionally provide additional features. Four types of features are defined by the BLE Mesh Profile: Relay, Proxy, Friend and Low Power. A Relay node is able to forward received messages and thus, enabling the multi-hop communication. Proxy nodes provide a Generic ATTribute (GATT) Profile interface to enable BLE devices that do not support the BLE Mesh Profile to interact with a BLE mesh network. The Proxy Protocol is defined by the BLE Mesh Profile and Proxy nodes translate messages from the non-mesh BLE devices in BLE mesh messages and vice versa. Friend and Low Power nodes work hand in hand: The Low Power node uses a low duty cycle to conserve as much energy as possible for a given use case. Nevertheless, a Low Power node needs to receive messages at any time, e.g. configuration messages from a user. Therefore, the Friend node receives messages that are destined for the Low Power node and stores them temporarily. In an active phase the Low Power node polls its Friend node for missed messages while sleeping. The relationship between both nodes is called friendship in the context of the BLE Mesh Profile. A node can support from zero to all features and each feature can be arbitrarily enabled or disabled [56]. A resulting BLE mesh network topology is depicted in Fig. 5. The basic mesh operation entirely relies on the BLE states advertising and scanning and thus, the nodes are not connected in the conventional Bluetooth sense [57,60]. This is a distinct property of BLE mesh networks in contrast to Bluetooth scatternets [56]. Consequently, BLE mesh networks do not take advantage of the FHSS technology and the TDMA MAC scheme. The message delivery in BLE mesh networks is implemented through “managed flooding”. Every node in a BLE mesh network receives all messages sent by nodes in its radio range. Nodes with the Relay feature activated forward messages to all nodes in their vicinity. Consequently, a destination node may receive a message through several paths. This behavior increases the reliability and is the main reason why flooding was preferred over explicit routing [56]. However, pure flooding causes a lot of overhead and thus, some mechanisms were integrated to optimize the flooding approach in BLE mesh networks. Each node periodically sends so-called heartbeats to indicate its presence. The heartbeats can be also used by receiving nodes to determine the number of hops distance to the heartbeat originator. A second mechanism is a Time-To-Live (TTL) counter for messages that defines the maximum number of hops a message should pass. Based on the knowledge gathered from the heartbeat messages nodes can effectively use the TTL counter to reduce the flooding overhead. A message cache is a third mechanism introduced to optimize the message flooding: Each node maintains a message cache that contains all recently received messages. On reception of a message that is already present in the cache the message is discarded immediately [56]. The relevance of a received message is verified at each node at different stack layers to discard a message as early as possible and thus, conserve as much energy as possible. As soon as a message is identified as irrelevant or damaged it will be discarded [56].

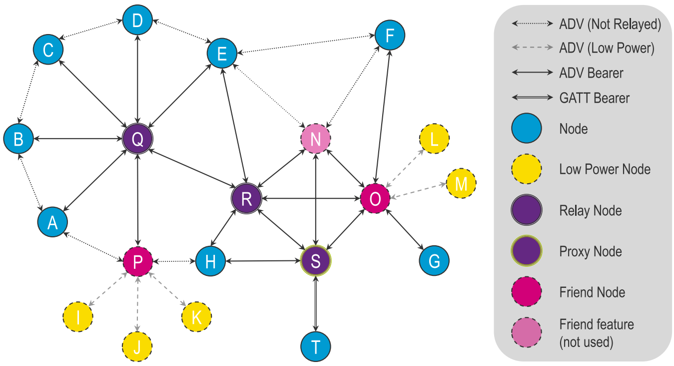

Fig. 5. Sample BLE Mesh Profile multi-hop network topology: Nodes A to H are BLE mesh nodes without a special feature whereas nodes I to M are BLE nodes with the Low Power feature activated. Their corresponding Friend nodes are nodes O and P respectively. Node N also has the Friend feature enabled but currently, no Low Power node uses it. The nodes Q and R relay messages and thus, the Relay feature is enabled. The Proxy node S transforms messages received from the non BLE Mesh Profile node T and relays them subsequently [59].

4. Scatternet formation

Scatternet formation concepts are only required for connected Bluetooth multi-hop networks referred to as scatternets. Classic Bluetooth differs from common wireless ad-hoc technologies in providing no shared broadcast medium [61]. Even if all devices are in radio range of each other only classic Bluetooth devices synchronized to a transmitting device will be able to receive a message [61]. Furthermore, even though Bluetooth devices have the same range of functions Bluetooth communication is based on point-to-point connections and a master-slave model [62]. Slave devices are not able to communicate directly and a master is only able to coordinate a set of active slaves at a time. In conventional wireless multi-hop networks nodes are supposed to act symmetrically [63]. Consequently, in Bluetooth multi-hop networks there are two kinds of topologies: a physical and a logical one. The physical topology is determined by the deployment of the Bluetooth nodes, the communication range of the nodes and the geometry of the surrounding environment [11,62]. Whereas the logical scatternet topology has to be explicitly established [64] and is the result of scatternet formation mechanisms [11].

A scatternet formation mechanism has to configure all nodes of a network in a way that all pairs of nodes together form a connected topology [61]. At the beginning of the network formation process all nodes are isolated and have no knowledge about other nodes in the network [65]. A scatternet formation procedure groups the nodes into piconets and selects bridge nodes to interconnect the piconets [61]. This comprised the selection of master, slave and bridge roles for all devices. The lowest requirement on the resulting topology is connectivity [11] which means that there has to be at least one path between arbitrary devices [61]. But to guarantee even connectivity is NP-hard due to the constraints imposed by Bluetooth's characteristics [62].

The properties of the resulting topology have a great impact on the performance of the scatternet [66–69]. Augel and Knorr mentioned that there are over one million possible scatternet topologies with only 10 Bluetooth devices in radio range but most of these topologies are inefficient ones [70]. Over the years many preferable properties of a scatternet topology were identified. The following list records the most important ones:

- connectivity [61,65]
- limited number of piconets [61,71]
- limited number of slaves per piconet [72,73]
- limited number of bridges per piconet [73]
- limited number of bridges between piconets [61,73]
- limited network diameter [72,74]
- limited number of or no master/slave bridges [73,75,76]
- limited number of piconets per slave [74,76]
- limited number of roles per node [72]
- limited number of node pairs that use a bridge node [2,74]
- reliability (more than one path between arbitrary nodes) [77]
- maximal throughput [2,73,78]

Moreover, the scatternet formation mechanisms should have several desirable properties that are summarized in the next list:

- distributed (do not rely upon a central entity) [71,74]
- autonomous (without human interaction) [78,79]
- asynchronous (no synchronization between nodes) [74]
- dynamic (support joining + leaving of nodes) [74]
- should work in multi-hop scenarios [70]
- scalable [80]
- limited setup time [61,72,74]
- limited message complexity (required control messages) [72,74]
- limited energy demand [77]

The first listing above only contains the most important preferable properties of a scatternet topology. Furthermore, the list includes competing goals like a limited network diameter and a maximal throughput: to achieve a limited network diameter the degree of nodes has to be maximized. But a maximized node degree is synonymous to a shared bandwidth among many nodes and thus, to a reduced throughput [73]. Different investigators have an individual opinion about suitable, efficient and beneficial properties [70,73]. As a consequence a multitude of scatternet formation mechanisms was proposed during the last years [81]. Each of the proposed approaches focuses on a small number of scatternet topology metrics only Jedda et al. [81]. The Tables 2 and 3 classify the most important scatternet formation mechanisms using only some key properties to provide a clear overview. There are several very comprehensive surveys discussing individual approaches and design goals in detail: Augel and Knorr categorize the approaches published until 2004 into five categories (tree, mesh, ring, graph theoretical analysis and further approaches) [70]. Persson et al. distinguish between mechanisms requiring a single-hop or multi-hop environment and the single-hop solutions are further classified into coordinated and distributed approaches. Besides a very good tabular overview of reviewed formation mechanisms they also provide an explanation of the individual mechanisms [80,183]. Moreover, the second version of this survey ([183]) also contains many basics of Bluetooth technology. Vergetis et al. consider the problem of Bluetooth scatternet formation from an algorithmic perspective and finally provide a tabular overview comparing the reviewed approaches [62]. Wang et al. also classify a variety of existing scatternet formation mechanisms in the two main categories single-hop and multi-hop environment. In each group they further distinguish many subgroups and give a detailed description of the approaches [184]. A very comprehensive survey is provided by Whitaker et al. [2]. The work considers many details of Bluetooth technology in general, scatternet formation, routing and scheduling in scatternets. Many scatternet formation approaches are explained in detail and two tabular overviews of scatternet formation algorithms are provided. The most comprehensive one lists 23 scatternet formation mechanisms classified according to 20 aspects. The survey was published online in February 2004 and thus, only reviews approaches published until that time [2]. Stojmenovic and Zaguia also provide a detailed survey on scatternet formation mechanisms [185]. They keep the classification into single- and multi-hop approaches and categorize both groups further in several categories. The latest overview of scatternet formation mechanisms is given by Jedda et al. [16].

Tables 2 and 3 list the existing scatternet formation mechanisms using six aspects: the resulting topology of the scatternet formed, the ability of the mechanisms to work in a multi-hop environment, the property of the algorithm to work in a centralized or distributed manner, the ability to establish degree-limited piconets, the capability of the procedures to respond to topological changes and the way in which the approaches were evaluated.

The structure of the topology formed affects the performance of the resulting scatternet. We distinguish between tree, mesh, ring, shared slave topology (SST) and some hybrid structures. Fig. 6 visualizes the four basic topology types. In a tree topology the usage of master/slave (M/S) bridges is unavoidable [97]. The root node is the only node with a single master and all leaf nodes are the only nodes with a single slave role. All intermediate nodes are master/slave bridges. A tree topology provides connectivity with the minimal number of links [2,67]. There is only one path between any two nodes [67,97]. As a consequence the topology does not contain any loops [2,97]. Both facts simplify the packet forwarding [2,72,97,183]. But the disadvantage of the single path between any two nodes and the hierarchical structure is the high risk for network partitioning [2,76,183]. Furthermore, the parent nodes tend to be communication bottlenecks [97,183] and the root node is a single point of failure [76,115]. A ring topology provides two disjoint paths between any two nodes while ensuring a simple packet forwarding [67]. In fact, the packet forwarding mechanism is less complex than in tree topologies: incoming packets on one port just need to be forwarded to the other. In tree structures a simple forwarding table is required to remember to which outgoing connection a packet has to be passed. But the drawbacks of the ring topology are the longer path length and thus, longer packet delays [2,67,183] and the fact that a logical ring cannot be built on top of arbitrary physical topologies [2,67]. Ring topologies can be constructed using both types of bridge nodes (as illustrated in Fig. 6). Mesh topologies avoid the disadvantages of tree topologies at the expense of a higher routing complexity [72]. In general, both types of bridge nodes are possible for mesh structures. The shared slave topology (SST) can be regarded as a special case of a mesh structure. Any two piconets share a (slave) node [97]. As shown in Fig. 6 the shared slave can be a slave/slave or master/slave bridge. The shared slave topology maintains the well known star-shaped piconet topology: individual piconets are clearly visible just interconnected to neighboring piconets. A cube topology extends the mesh concept to three dimensional deployments [137].

In single-hop scenarios all nodes of the network are in communication range of each other whereas this is not true for multi-hop environments [183]. Centralized or coordinated approaches rely upon one distinguished entity that has the knowledge of the entire physical network topology and assigns roles and connections to all other nodes [141,183]. But the communication overhead to collect the global knowledge is high. Distributed mechanisms are executed independently on each node and require only local knowledge of the physical network graph [141], i.e. the one or two hop neighborhood information. Ideally, the protocols should be processed com-

Table 2
Classification of scatternet formation mechanisms I.

Name	Year	Topology	Multi-Hop	Distributed	Piconet degree-limited	Dynamic	Evaluation	Based on
SuperMaster [82]	2000	Mesh	✗	✗	n.a.*	✗	Simulation	–
Bhatnagar and Kesidis [83]	2001	Tree	✓	✓	✓	n.a.*	Simulation	–
MIT-BSFA [71,84–86]	2001	Mesh	✗	role assignment centralized	✗	only join	Analytical, Simulation	–
BTCP[61,87]	2001	Mesh	✗	role assignment centralized	✓	✗	Simulation	–
TSF [4,88–90]	2001	Tree	✗	✓	n.a.*	✓	Simulation	–
Blueroot Grown Bluetrees [91]	2001	Tree only ms-bridges	✗	✗	✓	✗	Simulation	–
Distributed Bluetrees [91]	2001	Tree	✓	✓	✓	✗	Simulation	–
Baatz et al. [78]	2002	n.a.*	✗	✓	n.a.*	✗	Conceptual	BTCP
BlueStars(1), BlueConstellation [92–95]	2002	Mesh	✓	✓	✗	✗	Simulation	–
BlueRing(1) [67]	2002	Ring	✗	✓	n.a.*	✗	Simulation	–
IBNF [96]	2002	SST	✓	✓	✓	✓	Simulation	–
BTSF[97]	2002	SST no ms-bridges	✓	✓	✓	✓	Simulation	–
Scatternet Route [98,99]	2002	n.a.*	✓	✓	n.a.*	implicit	Simulation	–
Marsan et al. [68]	2002	n.a.*	n.a.*	✗	n.a.*	n.a.*	Analytical	–
BlueMesh [100,101]	2002	Mesh	✓	✓	✓	✗	Simulation	–
Scatternet Operation Protocol [102,103]	2002	n.a.*	✓	✓	n.a.*	✓	Simulation	–
Yao protocol [5,104]	2002	Mesh	✓	✓	✓	✗	Simulation	–
Blue-tree [105]	2002	Tree	✗	✓	✓	✓	Conceptual	Blueroot Grown Bluetrees
BlueNet [106,107]	2002	Mesh	✓	✓	✓	✗	Simulation	–
Yugandhar[108]	2002	n.a.* no ms-bridges	n.a.*	✓	✓	only join	Simulation	MIT-BSFA
Bluestars(2) [63]	2002	SST	✓	✓	n.a.*	✓	Simulation	–
Barrière et al.[76]	2003	Mesh no ms-bridges	✗	✓	✓	✓	Conceptual	–
BlueCube [109]	2003	Hybercube	✗	✓	n.a.*	n.a.*	Simulation	–
SHAPER [110]	2003	Tree	✓	✓	n.a.*	✓	Simulation	TSF
Dharia and Agrawal [111]	2003	SST	✓	✓	✓	only join	Simulation	–
Dong and Wu[112]	2003	Tree	✓	n.a.*	✓	✗	Simulation	Blueroot Grown Bluetrees
MSF + SSF [113]	2003	Mesh	✓	✓	✓	✓	Simulation	–
ROM [114,115]	2003	Hybrid: Ring + Star no ms-bridges	✗	✗	✓	✓	Simulation	BTCP
HGB [116,117]	2003	Mesh	n.a.*	n.a.*	✓	n.a.*	Conceptual	–
RNG algorithm [11,62]	2003	n.a.*	✓	✓	✓	✓	Simulation	–
TPSF [118]	2003	Mesh	✓	✓	✗ (ctrl scatternet)	✓	Simulation	–
BlueRing(2) [119,120]	2003	Hybrid: Ring + Star	✗	✗	✓	partially	Analytical, Simulation	BTCP
SF-DeviL [121–123]	2003	Tree only ms-bridges	✓	✓	✓	✓	Simulation	–
Reading-Picopoulos and Abouzeid [124]	2003	Tree	✓	✓	✗	✓	Simulation	–
GSFA [125,126]	2003	Mesh	✗	role assignment centralized	✓	n.a.*	Simulation	MIT-BSFA
BTnet [79]	2003	Tree	✓	1st scatternet: ✓ optimization: ✗	✓ (can be violated)	n.a.*	Analytical	–
LSF [74]	2003	Hybrid: Ring + Star no ms-bridges	✗	✓	✓	✗	Analytical, Simulation	MIT-BSFA
TPSF+ [18,127]	2003	n.a.*	✓	n.a.*	✗	✓	Simulation	TPSF
Blue-Star Island [128]	2003	Mesh	✓	✓	n.a.*	✓	Simulation	–
LSBS [129]	2004	Mesh	✓	✓	✓	n.a.*	Simulation	BlueStars(1), Yao protocol
TreeNet [130,131]	2004	Tree	✗	✓	✓	✓	Real World	–

* not available.

Table 3
Classification of scatternet formation mechanisms II.

Name	Year	Topology	Multi-Hop	Distributed	Piconet degree-limited	Dynamic	Evaluation	Based on
Blueline [132]	2004	Mesh	✓	✓	✗	✗	Simulation	–
TCSF [133–135]	2004	configurable (Star,Mesh,Ring,Chain)	✗	✗	✓	n.a.*	Real World, Simulation	–
SHAPER-OPT [136]	2004	Mesh	✓	✓	✓	✓	Simulation	SHAPER
MSF [137,138]	2004	Mesh + Cube (3D)	✗	✓	✓	✓	Simulation	–
Bluepleiades [19,139,140]	2004	Mesh	✓	✓	✓	✗	Real World, Simulation	BlueStars(1)
BTSpin [141]	2004	Mesh	✓	✓	✓	✓	Simulation	–
BlueScouts [142]	2004	Tree	✓	✓	n.a.*	✓	Simulation	–
MBNET [143]	2004	Alternative Scatternet⋆ Mesh	✓	✗	✓	n.a.*	Simulation	–
Mehta and El Zarki [144]	2004	Tree	✓	✗	✓	✓	Simulation	–
ODBT [145]	2004	Tree only ms-bridges	✗	n.a.*	✓	✓	Simulation	Distributed Bluetrees
BTDSP [146,147]	2004	Mesh no ms-bridges	✓	✓	✓	✓	Simulation	–
Evolutionary SF [148]	2004	n.a.* no ms-bridges	✗	✗	✓	✗	Simulation	–
MTSF [149]	2004	Mesh no ms-bridges	✓	✓	n.a.*	✓	Simulation	–
Tekkalmaz et al.[150–152]	2004	SST no ms-bridges	✗	✓	✓	✓	Simulation	–
Wang et al. [153]	2004	n.a.*	✗	✓	✓	n.a.*	Simulation	Yao protocol
TreeNet+ [154]	2005	Tree	✓	✓	✓	✓	Real World	TreeNet
DMSFA [155]	2005	Tree	✓	✓	n.a.*	✓	Simulation	SHAPER
eBlueScatter [156]	2005	Mesh	✓	✓	✓	n.a.*	Simulation	–
Saginbekov and Korpeoglu [157]	2005	Tree	✓	✗	✓	✗	Simulation	–
dBBlue [158]	2005	Mesh	✗	✗	✓	✓	Conceptual	*Barrière* et al.
Zhang and Riley [159,160]	2005	n.a.* no ms-bridges	✓	✓	n.a.*	implicit	Simulation	Scatternet Route
BluePower [161]	2005	Mesh	✓	✓	✓	✓	Simulation	–
Bluepleiades⋆ (SS-Blue) [162]	2006	Mesh	✓	✓	✓	n.a.*	Simulation	Bluepleiades
Chou et al. [163]	2006	Tree	✓	✓	✓	✓	Simulation	–
OBP [164,165]	2006	Virtual Scatternet	✓	✓	n.a.*	implicit	Simulation	–
ETSF [166–168]	2006	Tree	✗	✓	✓	✓	Simulation	–
BlueMIS [169]	2007	Mesh	✓	✓	✗	✓	Simulation	BlueMesh
BBSF [170,171]	2007	Tree	✓	✓	n.a.*	✓	Simulation	–
EMTS [172]	2007	Tree	✓	✓	✓	✓	Simulation	–
TPSF+C [173]	2008	SST (ctrl scatternet), no ms-bridges (ctrl scatternet)	n.a.*	n.a.*	✗ (ctrl scatternet)	n.a.*	Simulation	TPSF+
BlueHRT [174,175]	2009	Hybrid: Ring + Tree	✓	✓	✓	✗	Simulation	–
M-dBBlue [176]	2009	Mesh	✓	n.a.*	✗	✓	Simulation	dBBlue
Enhanced Bluetree [177]	2010	Hybrid: Mesh + Tree	✓	n.a.*	✓	n.a.*	Simulation	–
BGN [178]	2011	Mesh	✓	✓	✓	✗	Simulation	–
SFX [179]	2011	Tree	✓	✓	✓	✓	Real World, Simulation	SHAPER
BSF-UED [13,81]	2013	Mesh	✓	✓	✗	n.a.*	Simulation	BlueStars(1), BlueMesh, BlueMIS
Guo et al. [22]	2015	Mesh	✓	✓	–	✓	Real World	BLE
FruityMesh [180]	2015	Tree	✓	✓	–	✓	Real World	BLE
Jung et al. [181]	2017	Mesh no ms-bridges	✓	✓	–	✓	Simulation	BLE
Bluemob [182]	2017	Mesh	✗	✓	✓	✓	Simulation	MIT-BSFA

* Not available.

⋆ Each node is equipped with at least two Bluetooth devices.

pletely independent on each node, especially without synchronization between nodes. But it is very difficult to determine the resulting overall topology in this way. Thus, many approaches are divided in different phases to use loose synchronization at least [2]. Centralized approaches have a limited practical benefit but produce optimal topologies with respect to particular performance metrics [2,69].

The fourth aspect in the tables indicates whether the scatternet formation mechanisms produce piconet-degree limited scatternet topologies. A master node in a classic Bluetooth piconet is only able to coordinate seven active slaves at a time. If there are more than seven slaves in a piconet the master will be able to park a slave to enable another slave to participate actively. The parked slave is not able to communicate unless it is unparked by the master again. Parking and unparking are very time consuming procedures that should be avoided with respect to the performance of the scatternet [5]. By limiting the number of slaves per piconet to less than eight the park/unpark procedures can be averted. Furthermore, the PARK state of classic Bluetooth has been conceptually discarded since classic Bluetooth Core Specification version 5.0 and thus, only scatternet formation mechanisms for the classic Bluetooth technology that avoiding the use of the PARK state are sustainable.

Static scatternet formation mechanisms assume a fixed physical topology and that all nodes are powered simultaneously or within a short period of time. Dynamic approaches are able to handle joining and leaving nodes at arbitrary times [141]. Consequently, dynamic mechanisms are considered to be self-healing - provided that the physical topology allows for it. Against the background of wireless ad-hoc networks dynamic approaches are more attractive

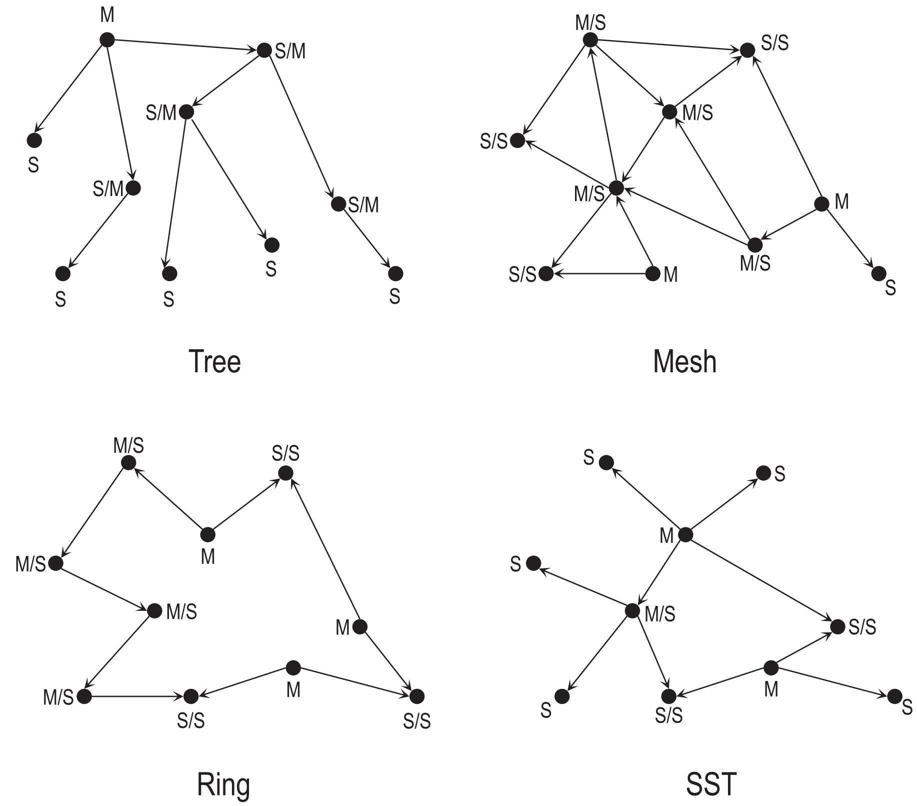

Fig. 6. Visualization of the four basic logical topologies tree, mesh, ring and shared slave topology (SST). Directed connections represent master-slave relations: the arrow points towards the slave. Bridge nodes are either of master/slave (M/S) or slave/slave (S/S) type.

for real world deployments because of probable modifications of the physical network topology due to mobility effects, link or node failure.

The Tables 2 and 3 list 81 scatternet formation mechanisms. The properties of the mechanisms in Tables 2 and 3 are based on details given in the publications. Thus, some properties are just stated or given as objective but often it is not proven that the property or objective is achieved in any case. The majority (85.2%) of them are evaluated analytically or by simulation. Some of the proposed approaches (6.2%) are described conceptually solely. Only seven (8.6%) of the concepts are implemented in real world scenarios.

According to Guerin et al. [11] Bluetooth scatternet formation was addressed for the first time by Salonidis et al. presenting their Bluetooth Topology Construction Protocol (BTCP) in 2001 [61]. The BlueStars(1) [95] mechanism is the fastest distributed multi-hop protocol according to [10] but it produces a scatternet with an unbounded number of slaves per piconet. This drawback was tackled by Stojmenovic and Li et al. with their so-called Yao protocol [5,104]. It was the first scatternet formation approach that produces connected scatternets in a multi-hop scenario in a distributed way with a limited number of slaves per piconet to completely avoid parking and unparking procedures. But this benefit was achieved at the expense of needed node position information. It is assumed that each node is aware of its position and the positions of its neighbors. Stojmenovic and Li et al. mention the Global Positioning System (GPS) and an estimation of the relative node distances based on received signal strength as candidates to maintain the nodes' positions. But no details are given and the existence of nodes' location information is just supposed throughout the paper. The same is true for the Li-Stojmenovic/BlueStars(1) (LSBS) mechanism [129] which is a combination of BlueStars(1) and the Yao protocol: it solves the disadvantage of BlueStars(1) but requires node position information (inherited from the Yao protocol) [140]. The mechanisms Bluetooth Hybrid Ring Topology (BlueHRT) proposed by Al-Kassem et al. [174] and the one presented by Dong and Wu [112] rely upon location information of the nodes, too. BlueMesh [101] provides a scatternet formation procedure to create connected scatternets with limited number of slaves per piconet without requiring position information. Instead the protocol needs the two-hop neighboring information [176] and several iterations which increase the time and message complexity [140].

Cuomo et al. claim in their presentation of the **S**elf-**H**ealing **A**lgorithm **P**roducing multi-hop Bluetooth scatt**ER**nets (SHAPER) approach that it is the first self-healing scatternet formation mechanism. It produces scatternets with a tree topology [110]. The Hierarchical Grown Bluetrees (HGB) [117] avoid the three disadvantages of a general tree topology: long path lengths, tendency of parent nodes to become communication bottlenecks and the vulnerability against network partition. The tree grows level by level which allows for balancing the tree. Furthermore, connections between siblings are permitted. The drawback is the loss of one of the main advantages of the tree naming the absence of loops. This renunciation significantly increases the complexity of routing mechanisms.

A first real world evaluation of a distributed multi-hop scatternet formation algorithm was presented by Beutel et al. They propose the TreeNet+ mechanism [154] and implemented it on 71 nodes. Their predecessor approach TreeNet [131] used a previous version of the hardware platform and thus, was restricted to single-hop scenarios. Methfessel et al. went even further in integrating their Solarflex (SFX) scatternet in a real world application. They reported the successful deployment of 39 nodes in a photovoltaic power plant [186]. The SFX scatternet formation mechanism [179] firstly uses the Extended Inquiry Response mechanism introduced in Bluetooth Core Specification version 2.1. This clue significantly simplifies the scatternet formation process. There is no need to establish a connection between two nodes to exchange information required for the scatternet formation algorithm solely. It can just be exchanged during the inquiry procedure with all nodes in vicinity. The idea to avoid an establishment of unnecessary Bluetooth connections was first mentioned by Marsan et al. [68] in 2002 by using some free bits of the Frequency Hop Synchronization (FHS) packet to exchange additional information during inquiry.

Most of the scatternet formation mechanisms proposed are proactive: a connected scatternet topology is established right after powering the nodes [127,173,187] and it is maintained continuously [127]. The scatternet constructed is used to transfer control as well as application data [187]. Only some of the existing scatternet formation procedures are reactive ones: Scatternet Route [98,99], Blue-Star Islands [128], On-Demand BlueTooth scatternet formation algorithm ODBT [145] and the mechanism of Zhang and Riley [159,160]. In reactive approaches a path between two nodes is only established if the nodes want to communicate [127,173]. In this case the path is constructed by building a scatternet structure. The advantages of reactive mechanisms are the dramatic reduction of the amount of control messages [188] and thus, the reduced energy required [159,188] and the shorter path lengths [187]. The drawback of the reactive procedure is the higher delay necessary to establish a path between source and destination before data communication can occur [159]. There are also a few hybrid schemes that try to exploit the advantages of both worlds: the short delay of the proactive mechanisms and the reduced amount of control messages of the reactive ones [173]: Two Phase Scatternet Formation (TPSF) [118], new Two Phase Scatternet Formation (TPSF+) [127] and enhanced Two Phase Scatternet Formation (TPSF+C) [173]. All of these approaches use a control and an on-demand scatternet [173,188]. The control scatternet is established proactively [188] and acts as a backbone whereas the on-demand scatternet will be established if two nodes want to communicate [188]. The control scatternet is used to transfer control messages and the on-demand scatternet is used to transfer the application data [173]. By using the control scatternet the delay to establish the on-demand scatternet can be reduced [173].

The reliability of the scatternet is tackled at different levels by the mechanisms in Tables 2 and 3. There are some inherent reliability-related properties of the topology used as described earlier in this section. A meshed topology ensures the highest degree of reliability and 40 scatternet formation mechanisms construct this kind of topology. Without special care a tree topology is per definition the most vulnerable topology and 23 mechanisms generate a tree topology. Five mechanisms listed in Tables 2 and 3 use a hybrid topology to combine advantages of different topologies. A scatternet formation mechanism should incorporate concepts to support nodes joining and leaving. In the Tables 2 and 3 this property is denoted as “dynamic”. 44 of the mechanisms listed are able to react on topology changes. Because there are so many scatternet formation approaches published that do not handle dynamically modifications of the topology mechanisms were proposed that assume a scatternet already built. These approaches are described in the next Section 5. Some scatternet formation mechanisms further address the scatternet’s reliability. Three groups were identified: The first group tries to balance the energy resources of the nodes to prolong the lifetime of the scatternet. The mechanism by Yugandhar [108], Energy-efficient Tree Scatternet Formation (ETSF) [168] and Energy-aware Multi-hop Tree Scatternet (EMTS) [172] belong to this group. A second approach is to balance the traffic load among the nodes and thus, indirectly tackle the same goal as group one: prolong the scatternet’s lifetime. The mechanisms of Dharia and Agrawal [111] and Saginbekov and Korpeoglu [157] address the traffic load balancing. The mechanisms of the third group explicitly try to enhance the scatternet’s connectivity. Barrière et al. [76] construct a scatternet topology that explicitly have a high connectivity. They call the group of scatternet topology built “projective scatternets”. In BTSpin [141] Ghosh et al. maintain information about backup gateways that can be used when a bridge node fails. The SFX [186] mechanism monitors the path loss of links and tries to find another path if the path loss is above a configurable threshold. Of course, a (partial) restructuring of the tree topology is required. The mechanisms eBlueScatter[1] [156] and **S**catternet **F**ormation algorithm based on **Devi**ce and **L**ink characteristics (SF-DeviL) [121] use a combination of group one and three by selecting links that cover nodes with high energy resources and a high received signal strength.

Scatternet formation mechanisms for devices using BLE were presented by Guo et al. [22], 201 [180] and Jung et al. [181]. The essential difference to classic Bluetooth formation concepts is the usage of the shared broadcast channel at regular intervals to detect and exchange modifications of the physical neighborhood.

In literature some approaches are discussed that have the objective to find optimized scatternet topologies: [63,68,69,75,78,104]. According to Persson et al. [183] their practical relevance is negligible but they provide relevant insights to theoretical backgrounds of scatternet formation.

It is obvious that there are a plenty of scatternet formation mechanisms proposed in recent years. According to Hodge and Whitaker it is difficult to compare different approaches because every research group uses individual design objectives and evaluation criteria. Therefore, they present a framework that aims to close this gap [73].

5. Scatternet’s topology maintenance and optimization

Maintenance and optimization of a scatternet topology are closely related to the scatternet formation process and thus, are only needed for connected Bluetooth networks. Approaches of this group assume an existing scatternet topology (already formed by a scatternet formation algorithm) to work on. Because the topology maintenance and optimization mechanisms are not intended to build a scatternet starting from a set of isolated nodes they are discussed in this separate section. Some of the approaches deal with the topology maintenance topic whereas the majority proposes mechanisms to optimize a given scatternet topology with respect to a certain optimization goal. Topology maintenance procedures define rules to handle modifications of the topology, i.e. nodes joining or leaving the scatternet. Table 4 lists the identified publications classified according to the scatternet’s topology, single- or multi-hop scenario, centralized or distributed approach and the way the procedure was evaluated. The approaches for topology maintenance were of interest because there are many scatternet formation mechanisms that are not able to react on topology changes as discussed in Section 4.

Subject of the topology optimization approaches is the restructuring of a given scatternet topology to achieve an individual goal. The suitability of a scatternet topology is dependent on various aspects. First of all an ad-hoc network is dynamic in nature - nodes join and leave due to mobility, failure or varying channel conditions at arbitrary times [189,190]. But there are other factors like traffic characteristics, path lengths, shared bridge nodes etc. that influence the performance of a scatternet [189,191]. A topology that is suitable at one time can be sub-optimal at another [191]. As can be seen in Table 5 the investigators of optimization mechanisms strive after many different goals but the mechanisms used to realize the reorganization of the topology are the same:

- link setup
- link teardown
- role switch

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[1] acronym has no one-to-one meaning.

Table 4
Classification of scatternet's topology maintenance mechanisms.

Name	Year	Topology	Multi-Hop	Distributed	Evaluation	Based on
Chiasserini et al. [69]	2003	n.a.*	n.a.*	✓	Conceptual	*Marsan* et al.
Chiasserini and Marsan [207]	2005	mesh + tree(different algorithms)	✓	✓	Simulation	–
RNV + EN [208]	2006	arbitrary	✓	n.a.*	Real World	–
MOLAR/ROMA [192,193]	2008	mesh	✓	✓	Simulation	–
LRIC [209]	2012	n.a.*	✓	n.a.*	Simulation	–

* not available.

Table 5
Classification of scatternet's topology optimization mechanisms.

Name	Year	Goal	Multi-Hop	Distributed	Evaluation	Based on
TDSO [191]	2001	Increase capacity	✗	✓	Simulation	–
Duggirala et al. [199]	2003	Balance bridge load, increase scatternet lifetime	n.a.*	n.a.*	Simulation	–
BEAM [210]	2003	Bridge selection framework	n.a.*	n.a.*	Conceptual	–
Bhargava and Gruenbacher [203]	2004	Avoidance of inter-piconet interference	n.a.*	n.a.*	Simulation	–
ARSP [202,211]	2004	Reduce packet loss + transmission delay	✗	✓	Simulation	–
SHAPER-OPT (SHAPER+DSOA) [212–214]	2004	Reliability (tree → mesh), maximize capacity, minimize path length	✓	✓	Simulation	SHAPER
Kallo et al. [190,215]	2004	Increase throughput, reduce delay, energy consumption + communication overhead	✓	✗	Simulation	BlueStars(1)
ANF [216]	2004	Adapts the routes to the needs of the data streams	✗	✓	Conceptual	–
HDSCA [217]	2004	Minimize average delay	n.a.*	✓	Analytical	–
TARP [218]	2005	Reduce traffic load, increase throughput	✓	✓	n.a.*	–
Jung et al. [189,219]	2005	Reduce path length	n.a.*	✓	Simulation	–
RRDR (LORP) [198]	2007	Bridge node reduction	✓	✓	Simulation	–
PRP [220]	2008	Balance the traffic load, reduce path length	✗	✓	Simulation	–
DSRS [204]	2010	Bridge node reduction, network stability	n.a.*	n.a.*	Simulation	–
Lin and Wang [221]	2010	Reduce traffic load	✓	✓	Simulation	Tree Topology
DENM, SRNP, FRST [194–196], SFM [206]	2011	Reduce control overhead through backup bridges	✓	n.a.*	Simulation	–
DCC [200], CATC [201]	2011	Balance master and bridge traffic load through network restructuring and backup bridges	✓	n.a.*	Simulation	–
BNR [222]	2012	Reduce path length	✓	n.a.*	Simulation	–
HCSRR [223]	2013	Avoid congestion	✓	n.a.*	Simulation	–
ERMP [205]	2016	Network stability	✓	n.a.*	Simulation	–

* not available.

Some approaches rely upon position information: MObility based Location Aware Route (MOLAR)/ROute Maintenance Algorithms (ROMA) [192,193], Dynamic Energy-Aware Network Maintenance (DENM) [194], Self Reorganizing Network Protocol (SRNP) [195] and Flexible Relay Selection Technique (FRST) [196]. Except MOLAR/ROMA all of these assume that each node is aware of its location with the help of Bluetooth Location Networks (BLN) proposed by Gonzalez-Castano and Garcia-Reinoso [197]. The approach MOLAR/ROMA assumes the combination of Radio-frequency identification (RFID) technology and BLN to determine a node's position.

A total of nine publications originates from one research group around Bakhsh and Tahir. All their approaches are based on the identical idea taken from Relay Reduction and Disjoint Route (RRDR) (also denoted as LORP[2]) [198] to remove unnecessary bridge nodes. But in contrast to RRDR they do not discard the information about unnecessary bridge nodes but use them as backup bridges. The activation of backup bridges depends on the optimization goal and makes the difference in the publications.

The optimization mechanisms presented in Table 5 use different optimization goals. Some of them address the scatternet's reliability: The first group aims in prolong the scatternet's lifetime. The approach proposed by Duggirala et al. [199], Dynamic Congestion Control (DCC) [200] and Cross-layer-based Adaptive Traffic Control (CATC) [201] belong to this group. A second aspect affecting the reliability is to reduce packet loss. This goal is tackled by the mechanism Adaptive Role Switching Protocol (ARSP) [202]. The reduction of inter-piconet interference also increases the reliability of the scatternet and is discussed by Bharagava and Gruenbacher in [203]. Mechanisms of the fourth group address the improvement of the scatternet's stability. The approaches Dynamic Stable Relay Selection (DSRS) [204], Efficient Route Maintenance Protocol (ERMP) [205], RRDR [198] and Flexible Relay Selection Technique (FRST) [196] target to increase the network's stability. The mechanisms DENM, SRNP and Scatternet Formation and Maintenance (SFM) [206] all use the same concept: Backup bridges are activated before a link is broken or to recover a lost link.

The Tables 4 and 5 list 25 mechanisms. The majority (76%) of approaches was evaluated using simulation. Three proposals were described conceptually and one procedure was evaluated analytically. Only one approach (Recovery Node Vector (RNV) + Entry Node algorithm (EN) [208]) was evaluated via a real world implementation.

6. Inter-piconet scheduling

The basic connected Bluetooth topology is a piconet consisting of a master and a set of active slaves. The master coordinates the medium access within a piconet through Time Division Multiple Access (TDMA) by applying polling. In the context of Bluetooth polling is also known as intra-piconet scheduling [44]. Bridge nodes participate in different piconets in a time division multiplex manner to ensure the multi-hop packet forwarding. The inter-piconet scheduling determines the way the bridge nodes divide their time to their piconets. Obviously, inter-piconet scheduling is required in connected Bluetooth networks referred to as scatternets. The fundamentals of inter-piconet scheduling are defined for

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[2] acronym has no one-to-one meaning.

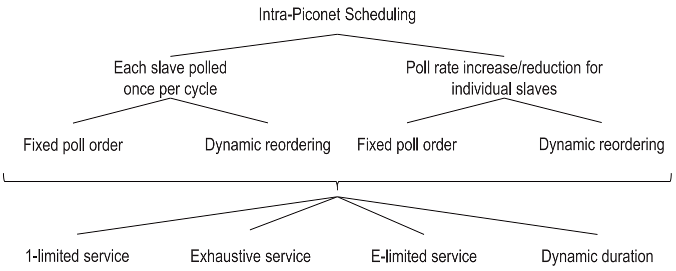

Fig. 7. Classification of basic intra-piconet scheduling strategies. There are a plenty of different variations proposed but this classification should give a fundamental overview. The first two hierarchy levels differentiate the poll order of the slaves, the last level presents the different basic mechanisms to determine the duration of a data transfer between master and slave.

classic Bluetooth technology, but the main principles can be transferred to BLE as well.

A schedule is defined by [224] as a sequence of time slots (each of length of 625 µs) and each transmission is assigned to a time slot. Bluetooth technology is connection-oriented. Thus, a transmission of one node is destined for one particular destination node [224]. That implies that two nodes have to be active in a scheduled time slot: the sender and the receiver node. Within a piconet these two nodes are the master and a slave. The intra-piconet scheduling strategy (polling) defines when each slave is allowed to communicate with the master and for how long. The Bluetooth specification does not define a specific polling strategy [225]. Consequently, many approaches were proposed and evaluated in the past. An intra-piconet scheduling mechanism has to address two main aspects: the order in which the slaves are polled and the duration the communication between the master and each slave should last [225]. According to these two aspects the existing polling strategies can be categorized (see Fig. 7). The second and third level of the hierarchy are given by the slave order. Basically, a sequence in which the master polls a number of slaves that matches the total number of slaves of the piconet is referred to as cycle [225] or polling cycle [2]. The second level of hierarchy differentiates between the structure of a cycle: in the first case each slave is polled once per cycle whereas it is possible to skip individual slaves for a sequence of or for individual cycles or to poll slaves multiple times in the second case [225]. The third level of hierarchy describes the order in which slaves are polled by the master: fixed and dynamic poll orders are possible. In fixed slave order mechanisms the slaves are polled in a regular order. In dynamic reordering polling strategies the order of the slaves is determined in a dynamic fashion - right before individual cycles or a sequence of cycles. Concerning the duration of the communication between master and each slave there are four basic schemes presented in the fourth level of hierarchy in Fig. 7: 1-limited service, exhaustive service, E-limited service and a dynamic duration. The structure of Fig. 7 means that each of the four basic schemes to determine the duration of data transfer between master and slave can be applied in each of the four groups determined by the polling order. In 1-limited service the master polls the slave in one time slot and the slave answers in the next time slot. Afterwards, the master continues polling the next slave according to the poll order. A master polls a slave until there are no more packets to exchange in exhaustive service and only then moves to the next slave. In E-limited service the master polls the slave until one of the following two conditions is met: 1) there are no more packets to send or 2) a specified maximum number of M packets was sent [225]. 1-limited and exhaustive service can be regarded as special cases of E-limited service with M=1 and M=max respectively [225]. Mechanisms that use dynamic data exchange duration determine the duration for each slave before each cycle in a dynamic fashion [226]. In the past years a huge amount of intra-piconet scheduling strategies was proposed and evaluated. According to [115] the substantial result is that dynamic strategies that are able to react to variable traffic characteristics are most efficient.

A Bluetooth scatternet is composed of interconnected piconets. Interfaces between piconets are Bluetooth nodes that are member of more than one piconet: the bridge nodes. Bridges apply time division multiplex to communicate in different piconets. Each piconet is coordinated by its master: the master determines the timing and the frequency hopping sequence [3]. Consequently, bridge nodes have to synchronize to different piconet properties when switching between piconets. Each piconet in a scatternet is autonomous and has especially its individual clock base. Accordingly, time slot boundaries of different piconets in a scatternet are not aligned [3] which is also referred to as phase difference [54]. As a consequence, a bridge node has to wait until the beginning of the next even numbered time slot after each piconet switch to participate in the entered piconet [3]: if the bridge is the master in this piconet the bridge will be allowed to transmit in even numbered time slots and if the bridge is slave in this piconet the bridge will have to wait which slave is addressed by the piconet master in the next even numbered slot. Therefore, in the worst case a piconet switch wastes two time slots as a result of phase difference [3,227]. Obviously, piconet switches cause a switching overhead. A trade-off regarding the frequency of piconet switches is required. Frequent switches cause a considerable amount of switching overhead whereas rare switches cause high packet delays (in particular concerning a transmission via several hops) [3]. The significant delay is accompanied by high memory demands to buffer packets waiting to be serviced.

An inter-piconet scheduling mechanism determines the points in time a bridge node switches between its piconets and the duration the bridge stays in each piconet [89,162,228]. The inter-piconet scheduling strategy has to balance carefully the frequency of piconet switches due to the trade-off described previously. The scheduling resources are Bluetooth time slots [227] as it is the case in intra-piconet scheduling. The definition of a schedule (sequence of time slots of fixed length and each transmission is assigned to a time slot) is extended in the scatternet configuration: transmissions that are assigned to time slots of a node participating in more than one piconet must not affect each other [224]. An interference of transmissions in a time slot is defined as conflict [224]. In a scheduling conflict situation a node is required to be active in more than one piconet in one time slot. The consequence of a scheduling conflict is that this node is not available in at least one of its piconets when it should be. Thus, the bandwidth in this piconet is wasted, the throughput reduced and the delay is increased. In intra-piconet scheduling a master divides its capacity onto its slaves through polling whereas a bridge node divides its capacity onto its piconets [229]. The degree of utilization of available slots of a bridge node depends on the scheduling strategy used [227] and therefore, the performance of the entire scatternet is determined by the scheduling [230,231]. The presence of a bridge node in all its piconets [232] should be coordinated in a way that optimizes the traffic within and between piconets [44]. But these goals are contradicting: the delay for intra-piconet traffic is reduced when piconet switches occur infrequently and the delay for inter-piconet traffic is reduced when the time between piconet switches is as short as possible [233].

Furthermore, a combination of intra- and inter-piconet scheduling is desirable [44,232]. As slave in a piconet a bridge node is polled by the master and appears as ordinary slave. Right after a piconet switch the bridge has to wait until the next even numbered time slot to figure out which slave is addressed by the piconet master. If the bridge node is not addressed right after a piconet switch the bridge node will have to wait until it is allowed to

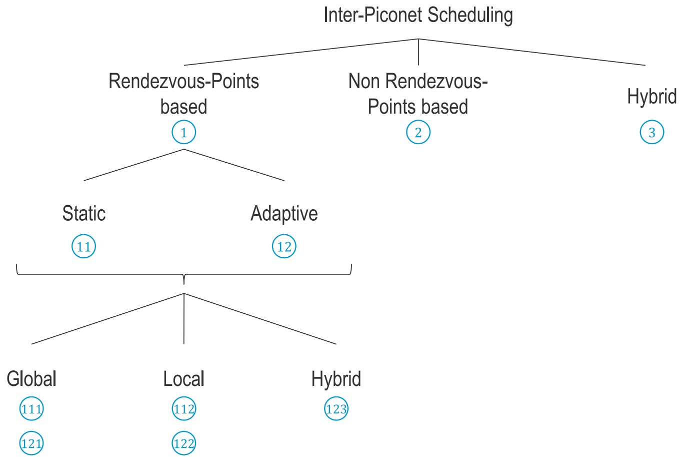

Fig. 8. Classification of inter-piconet scheduling strategies. The different groups are numbered (blue circles) and referred to in Table 6 that lists the most important inter-piconet scheduling approaches. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

communicate with the master. In this case, a piconet switch actually takes more than two time slots (switching overhead) regarding the inter-piconet traffic flow. Although synchronized to the entering piconet after two time slots the bridge has to wait until the data transfer can occur. This additional time is defined as bridge idle waiting time. Master nodes should be informed about bridge roles of nodes in their piconet to treat them in a beneficial way. The intra-piconet scheduling should take the inter-piconet scheduling into account to prevent polling a slave that is not active in the piconet [44] and to prevent bridge idle waiting times. Summarizing there are several aspects imposed by Bluetooth technology characteristics that make the development of efficient inter-piconet scheduling mechanisms challenging:

- each piconet is autonomous in a scatternet [234]
- no contention, but coordination through central entity in piconets [89]
- data transfer is based on TDMA but no global time reference in a scatternet [235]

The inter-piconet scheduling mechanisms should have the following desirable properties:

- mechanisms should be distributed and reliable [54]
- mechanisms should dynamically adapt to variable traffic conditions [234,236,237]
- mechanisms has to find a compromise for the frequency of piconet switches [237]
- the overhead necessary to realize the inter-piconet scheduling should be as low as possible [238]

Inter-piconet scheduling strategies should answer the questions when a bridge node should synchronize to all its masters and for which time duration the bridge should be active with individual masters against the background of different traffic characteristics, a different number of slaves and potential further bridge nodes in each piconet. The main metrics to evaluate inter-piconet scheduling mechanisms are overall network throughput, end-to-end packet delay, fairness and energy efficiency [89].

Inter-piconet scheduling mechanisms proposed in literature can be roughly classified according to three main characteristics: Rendezvous-Points based, non Rendezvous-Points based and hybrid approaches as presented by Fig. 8. Most of the existing solutions use so called Rendezvous-Points that are negotiated time slots between a master and a bridge node. The master commits to poll the bridge at these slots and the bridge agrees to be synchronized to the master's piconet [44,230]. The Rendezvous-Points based inter-piconet scheduling mechanisms should address two aspects: they have to determine how master and bridge decide about Rendezvous-Points and how long the interaction of master and bridge should last each time [44]. Bluetooth's modes SNIFF and HOLD can be used to implement the concept of Rendezvous-Points [225]. But it is also possible to use pseudo-random sequences of Rendezvous-Points [236,239]. Rendezvous-Points provide a basis to realize quality of service guarantees. An optimal schedule does not waste time slots and thus, scarce capacity [230]. But the construction of an optimal schedule for Bluetooth scatternets was shown by [224] to be NP-complete even provided that the following assumptions are satisfied: there is at least one link between all pairs of nodes, the requirements on all links are the same and the determination of the schedule is performed by a central entity knowing all information required for schedule computation a priori [224]. The high complexity of the scheduling task is caused by the fact that the operations performed by a node are dependent on the operations executed by all other nodes of the scatternet [224].

The goal of the utilization of Rendezvous-Points is to reduce idle waiting times [225]. Rendezvous-Points can be static - negotiated only once per scatternet lifetime [225] - or adaptive (cf. Fig. 8). Schedules consisting of static Rendezvous-Points will be advantageous if the traffic characteristics are known and invariant [240]. But for the majority of real world applications they are inappropriate [89]. The schedules of Rendezvous-Points can be global for the entire scatternet determined using global knowledge of all nodes or local relying upon local information only. With a global schedule a polled slave is active in the piconet assuredly and there are no Rendezvous-Points conflicts [235]. Hence, bandwidth guarantees are possible [235]. But determining a global schedule requires explicit signaling between the nodes [236,241] and a reevaluation of the schedule every time the topology or traffic characteristics change [236]. Consequently, the time needed to react on changing conditions is high [241]. Establishment of local schedules is significantly less complex [236]. But it is not possible to ensure that there are no Rendezvous-Points conflicts or unnecessary idle waiting times [241]. Building Rendezvous-Points schedules using local information solely correlate to the ad-hoc nature of Bluetooth scatternets [228]. The third hierarchy level of Fig. 8 contains a third group of Rendezvous-Points schedules: hybrid ones. The mechanism Flexible Scatternet-wide Scheduling (FSS) [242] establishes a global schedule in a first step and performs local optimizations in a second [242].

Bridges operate without explicit slot schedules in non Rendezvous-Points based schemes [225]. Several piconets of a scatternet are “loose-coupled” [243]. A master node polls all its slaves (including bridge nodes) according to the intra-piconet scheduling strategy. A data transfer will be feasible only if the bridge node is present in the piconet. If a bridge node does not answer the master will poll the next slave [225]. Non Rendezvous-Points based schemes do not require resources - i.e. time and communication - to construct and maintain the Rendezvous-Points based schedule [225,238]. Thus, this concept is suitable for large-scale scatternets, too [225]. As a drawback communication capacity is wasted due to idle waiting of the master in case a bridge is not present while polled [225,238]. And the end-to-end delay is increased as a result of waiting of bridges to be polled after a piconet switch [225].

In hybrid schemes the master and bridge nodes alternately use Rendezvous-Points based schedules and non Rendezvous-Points based schedules. Rendezvous-Points based schedules are used in case the traffic load is high. The overhead needed to construct and maintain the schedules is justified against the background of the amount of user data to service in contrast to non Rendezvous-based schemes. If the traffic load is low the overhead will be dis-

Table 6
Classification of inter-piconet scheduling mechanisms.

Name	Year	Group	RP	Adaptive	Local	Hybrid	Evaluation	Based on
Kazantzidis and Gerla [230,244]	2000	112	✓	✗	✓	✗	Simulation	–
APPD [3,241]	2001	122	✓	✓	✓	✗	Simulation	–
DSSA [224]	2001	122	✓	✓	✓	✗	Conceptual	–
JUMP mode [239]	2001	122	✓	✓	✓	✗	Conceptual	–
PCSS [236]	2001	112	✓	✗	✓	✗	Simulation	–
Rao et al. [231]	2001	112	✓	✗	✓	✗	Simulation	–
Son et al. [245]	2001	121	✓	✓	✗	✗	Simulation	–
LAA [232,246]	2002	12	✓	✓	n.a.*	n.a.*	Analytical + Simulation	–
MDRP [233]	2002	112	✓	✗	✓	✗	Simulation	–
Scatternet Route [98,99]	2002	122	✓	✓	✓	✗	Simulation	Scatternet Route
IARTSS/CTSA [247–249]	2002	122	✓	✓	✓	✗	Simulation	–
HDICA [250]	2002	122	✓	✓	✓	✗	Analytical + Simulation	–
TSS/LCS [89,240]	2002	122	✓	✓	✓	✗	Simulation	TSF/Tree
FSS [242]	2002	123	✓	✓	✗	✓	Simulation	–
Agbakwuru and Fapojuwo [234]	2003	122	✓	✓	✓	✗	Analytical	–
Joo et al. [251]	2003	122	✓	✓	✓	✗	Simulation	–
Kim et al. [54]	2003	122	✓	✓	✓	✗	Simulation	–
GOSS [227]	2003	122	✓	✓	✓	✗	Simulation	–
LASS/LAMS [252,253]	2003	122	✓	✓	✓	✗	Analytical + Simulation	–
AISA [254]	2003	122	✓	✓	✓	✗	Simulation	–
Salonidis and Tassiulas [235]	2003	111	✓	✗	✗	✗	Simulation	–
Kapoor et al. [229]	2004	122	✓	✓	✓	✗	Analytical + Simulation	–
Walk-in [228]	2004	2	✗	–	–	–	Analytical + Simulation	–
ASA [255]	2005	122	✓	✓	✓	✗	Simulation	–
DRP [256]	2005	121	✓	✓	✗	✗	Simulation	–
SS-Blue [162]	2006	122	✓	✓	✓	✗	Simulation	APPD, MDRP, Bluepleiades*
TASS [237]	2006	12	✓	✓	n.a.*	n.a.*	Simulation	–
GBS [257]	2007	121	✓	✓	✗	✗	Simulation	–
QIPS [258]	2007	122	✓	✓	✓	✗	Simulation	LAA
Yu et al. [238,259]	2007	3	✗	–	–	–	Simulation	–
RAS [115]	2008	122	✓	✓	✓	✗	Simulation	ROM
PIPS [260]	2008	12	✓	✓	n.a.*	n.a.*	Simulation	–
OPS [261,262]	2008	12	✓	✓	n.a.*	n.a.*	Simulation	–
RT-BLE [263,264]	2016	1	✓	n.a.*	n.a.*	n.a.*	Real World	BLE

* not available.

proportionate regarding the gain of the Rendezvous-Points based schedule [238].

Table 6 lists the most important inter-piconet scheduling mechanisms proposed in literature. Approaches are classified using the groups defined in Fig. 8. Almost all (around 94%) of the 34 approaches registered in Table 6 use Rendezvous-Points based schedules but only one of them was evaluated using a real world implementation. This fact is not coincidental: as long as the scatternet concept remains conceptual and fuzzy described by the Bluetooth specification the user has no choice concerning either the intra- or the inter-piconet scheduling. Bluetooth chip vendors implement well-defined procedures solely and users rely upon the functionality of their Bluetooth hardware. The available Bluetooth chips provide an intra-piconet scheduling strategy that in fact determines the resulting inter-piconet scheduling behavior. Some of the vendors implement and document some supplementary rules in order to determine the behavior in a scatternet configuration. Without these additional information it is extremely tricky to analyze, understand and predict the inter-piconet scheduling properties of a real world scatternet implementation and it is still challenging with them. Only one approach listed in Table 6 uses non Rendezvous-Points based schedules. In fact, this concept equals reality: a scatternet is built according to a formation algorithm used and the entire scheduling behavior is determined by the Bluetooth hardware selected. The key finding is the same for BLE devices: the scheduling is implemented by the Baseband Resource Manager [265] and thus, the hardware used determines the resulting inter-piconet scheduling behavior. But in contrast to classic Bluetooth technology there is no possibility to affect the scheduling by the smart utilization of low power modes. Instead, the BLE specification provides a parameter called Slave Latency to reduce the number of Connection Events a slave has to listen to the master [46]. Patti et al. propose an inter-piconet scheduling mechanism for BLE bridge nodes. They calculate the Connection Interval for each master node based on a constant number of slaves. Furthermore, they assume that the number of packets the master wants to exchange with each slave is known and that the BLE hardware employs a pure round robin scheduling of the master's slaves. This way, a bounded (worst-case) latency for a scatternet configuration can be obtained. However, there can be scheduling conflicts for BLE bridge nodes. Patti et al. propose the use of a feature of the Generic ATTribute (GATT) Profile to solve these conflicts: BLE connections can be activated and deactivated using this feature. For each Connection Interval only one connection of each bridge node is active [263].

7. Packet forwarding in Bluetooth multi-hop networks

Bluetooth multi-hop networks can be considered as a special type of wireless ad-hoc networks [105]. Data transfer between arbitrary nodes in the network is dependent on packet forwarding of intermediate nodes. In general, each node of a multi-hop network will have to be able to decide if a packet received is destined for itself or if the packet has to be forwarded. In the latter case, the mechanism used depend on the type of the Bluetooth multi-hop network: in connectionless networks neighboring nodes share a broadcast channel and thus, the packet is just resent. Dedicated mechanisms are necessary to limit the number of times a single packet is redistributed. In case of a scatternet each master node should know to which slave and each bridge node should know to which master or slave the packet has to be sent to ensure a successful data delivery [266]. Mostly, this capability is provided by a routing mechanism. Primarily, a routing protocol should determine paths that do not include loops and do not

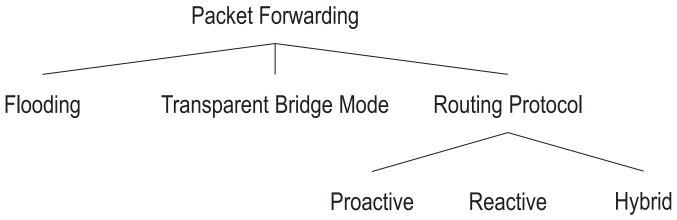

Fig. 9. Classification of packet forwarding concepts used in Bluetooth multi-hop networks.

lead to a blind end [267,268]. As secondary objective routing protocols should conserve a node's resources as much as possible [267]. Routing protocols depend on neighborhood relation information obtained from data link layer [269]. Ad-hoc routing protocols and thus, routing protocols for Bluetooth scatternets can be roughly classified in proactive, reactive and hybrid strategies (see Fig. 9). Furthermore, in Bluetooth scatternets there are network topologies that enable a simple packet forwarding based on the transparent bridge mode concept defined in the IEEE 802.1 D standard: nodes learn the incoming ports (Bluetooth connections) of originator addresses and use these information to forward packets only to these ports (Bluetooth connections) in case they receive a packet with a known destination address [270]. Forwarding a packet to all ports (Bluetooth connections of that node) except the input port (Bluetooth connection) will be only necessary if a node does not know the destination address [270]. But most topologies require a routing protocol to detect an unambiguous path [183]. Proactive and reactive routing protocols differ with respect to the point in time when a path is determined: proactive approaches identify paths to all potential destination nodes in advance as soon as the network is established [271]. So, routes are known before there is data to send [272,273] regardless of whether there will be data to send in the future. Thus, a route to an arbitrary destination is instantly available [274]. All the collected routing information is maintained and updated periodically [275]. Each modification of the network topology triggers an update process [276] and is propagated by system wide broadcasts [272] as soon as they are detected [272]. Thus, proactive routing protocols generate a high communication overhead [271,272] - especially expensive in networks with high node mobility [272]. Reactive routing strategies dynamically determine paths [2] just before a node wants to send data packets to a certain destination node [271]. Route discovery often performed by system wide flooding [105] is only required each time a new link is needed or an established link is invalid [277]. In contrast to proactive mechanisms the communication overhead is reduced significantly [247]. But this benefit is paid for the delay imposed by the route discovery process [247,274]. Hybrid routing protocols take the advantages of the proactive (no route discovery delay) and the reactive (lower communication overhead) world [278] often by dividing the network in clusters or zones [271]: within a cluster or zone a proactive mechanism is used and a reactive approach is adopted outside [271].

Most of the routing protocols tailored for general wireless adhoc networks implicitly assume IEEE 802.11 data link and physical layers [272] or claim to be independent from layers below [135] but they do not consider Bluetooth technology's characteristics [279–281]. Therefore, their direct operation in Bluetooth scatternets is inefficient [135,184,272]. Routing in wireless ad-hoc networks is difficult but due to the characteristics imposed by Bluetooth technology it is more difficult in Bluetooth scatternets [183]. The following list itemizes the Bluetooth characteristics that impact the routing process:

- Master/Slave concept and TDMA (polling)
- Connection-oriented technology and FHSS
- Master, slave and bridge roles of nodes in a scatternet
- Comparatively small packet sizes [105,279]

Bluetooth piconets are controlled by the master device that coordinates the medium access by polling its slaves and thus, deploys Time Division Multiple Access (TDMA). This aspect of Bluetooth technology has several routing related effects: slaves in a piconet are not aware of each other. They have information about their master(s) only [282]. Slaves in a piconet cannot communicate directly [282]. The master device has a connection to all of its active slaves and has the knowledge about all of its slaves. The throughput of one connection in a piconet decreases when the number of active slaves increases [281] and the throughput of a connection of a bridge device decreases when the number of piconets the bridge participates in increases [198]. Scatternets are connection-oriented and use the Frequency Hopping Spread Spectrum (FHSS) technology. Classic Bluetooth devices have no shared broadcast channel in the conventional sense [274,279]: the communication range of nodes does not indicate that nodes can hear each other [105,115]. Thus, it is necessary to establish connections to exchange routing information [274] (except for using the Extended Inquiry Response mechanism as demonstrated by Methfessel et al. [179]). Devices using BLE could use the three advertisement channels as shared broadcast medium. Furthermore, there is no scatternet wide time synchronization available and consequently, the use of timestamps is not straightforward [271]. The FHSS technology imposes a switching overhead for bridge nodes [198]. Established links are monitored by the Bluetooth technology but the temporal resolution of signaling of link states is not sufficient for higher layers [135,281]: although a link is indicated as available it can be already broken as long as the link supervision timeout has not expired [281]. Moreover, the indication of the existence of a link does not have a correlation to its link quality: the link quality can be so impaired that no data communication is possible [281]. The reason for this aspect is that control packets can be served but data packets not. Consequently, the number of hops is not a sufficient routing metric [135]. Finally, devices with different roles (master, slave, bridge) have different capabilities for packet forwarding because of many of these technology characteristics [281,283].

To make things more complicated, there are a plenty of scatternet formation mechanisms described in literature (cf. Section 4 and Tables 2 and 3) and the resulting topologies of these formation approaches have different properties [183]. The scatternet wide communication requires a routing protocol that is compatible to the scatternet formation mechanism used or is at least able to work on the established topology [284]. Consequently, it is very unlikely to agree on a generic scatternet routing protocol [183]. The underlying topology has a great impact on the performance of routing mechanisms [105,125,135,283]. There are scatternet topologies (tree, ring) that enable just packet forwarding and thus, the routing is considered as trivial in such topologies [183]. In a tree shaped scatternet the routing can be realized using a search tree [105] or using the Bluetooth Personal Area Networking (PAN) Profile and its part of the IEEE 802.1 D standard. The latter is also feasible for ring topologies. The PAN Profile uses the Bluetooth Network Encapsulation Protocol (BNEP). Both specifications have been active since February 2003. BNEP provides a scatternet-wide broadcast segment using the unique Bluetooth device addresses [44,115] and the PAN Profile takes the task of networking by using BNEP [115]. Indeed, in the active version only a single piconet PAN is supported [285] but different research groups ([179,281,286–288]) demonstrated that the approach also works in scatternet configurations.

As stated above, most scatternet topologies require a routing protocol instead of just forwarding packets [183]. Routing protocols designed for general wireless ad-hoc networks like Ad Hoc

Table 7
Classification of packet forwarding mechanisms.

Name	Year	Topology	Multi-hop	Routing	Reactive	Evaluation	Based on
RVM [279]	1999	Mesh	n.a.*	✓	✓	Conceptual	PARIS [291]
RDSR [292]	2001	n.a.*	✓	✓	✓	Real World	DSR [290]
Blueroute Layer [293]	2002	Mesh	✓	✓	✓	Simulation	DSR [290]
Lin et al. [9]	2002	n.a.*	✓	✓	✓	Simulation	X.25 [294]
Scatternet Route [98,99]	2002	n.a.*	✓	✗	–	Simulation	–
Prabhu and Chockalingam [295]	2002	Mesh	✓	✓	✓	Simulation	DSR [290]
Enhanced AODV [247]	2002	n.a.*	✓	✓	✓	Simulation	AODV [289]
Blue-tree [105]	2002	Tree	✗	✗	–	Conceptual	–
ROM [114,115]	2003	Ring + Star	✓	✗	–	Simulation	–
CORB [135,280,281,283]	2003	n.a.*	✓	✓	✓	Real World	AODV [289]
HGB [116,117]	2003	Tree	n.a.*	✓	✗	Simulation	–
BlueRing(2) [119,120]	2003	Ring + Star	✗	✗	–	Simulation	–
Kapoor and Gerla [272]	2003	n.a.*	✓	✓	hybrid	Simulation	ZRP [278], AODV [289]
BSR [274]	2003	n.a.*	✓	✓	✓	Simulation	–
TreeNet [130,154]	2004	Tree	✗	✗	–	Real World	Transparent Bridge Concept
Blueline [132]	2004	Mesh	✓	✓	✓	Simulation	AODV [289]
Blueweb [296]	2004	Mesh	✓	✓	hybrid	Conceptual	–
LARP [297,298]	2005	n.a.*	✓	✓	✓	Simulation	Location information
SCRP [299]	2005	n.a.*	✓	✓	✓	Simulation	CBRP [300] (DSR [290])
P2P-BlueTree [301]	2005	Tree	✓	✓	✗	Simulation	Prefix-based
Zhang and Riley [159,160]	2005	n.a.*	✓	✗	–	Simulation	Scatternet Route
SNR [302]	2006	n.a.*	✓	✓	✓	Real World	AODV [289]
M-dBBlue [176,303]	2006	Mesh	✓	✓	hybrid	Simulation	dBBlue, RIP [304]
Johansson and Carr-Motyckova [305]	2007	Mesh	✓	✓	✓	Simulation	A Control Scatternet
MOLAR [192], ROMA [193]	2007	n.a.*	✓	✓	✓	Simulation	Location information, LARP
RRDR (LORP) [198]	2007	Mesh	✓	✓	✓	Simulation	–
SNP [306]	2007	Mesh	n.a.*	✓	✗	Real World	–
LAMP [307,308]	2008	n.a.*	✓	✓	✓	Simulation	Location information
Solidring [309]	2008	Hyper Ring	✗	✓	✓	Coneptual + Simulation	–
P.A. AODV [282]	2009	Mesh	n.a.*	✓	✓	Simulation	AODV [289]
Li et al. [310]	2009	Mesh	✓	✓	✗	Conceptual	eBlueScatter
HBSR [284]	2009	Mesh	✓	✓	hybrid	Simulation	–
EMOLAR [311]	2011	n.a.*	✓	✓	✓	Analytical	MOLAR, Location information
SFX [179]	2011	Tree	✓	✗	–	Simulation, Real World	Transparent Bridge Concept
MHTS [312]	2013	n.a.*	✓	✗	–	Real World	BLE
Guo et al. [22]	2015	Mesh	✓	✓	✓	Real World	BLE
BSBR [313]	2016	Mesh	✓	✓	✓	Real World	BLE, DSR [290]
ALBER [12]	2016	DODAG (Tree)	✓	✓	✗	Real World	BLE, RPL [314]
CORP [181]	2017	Mesh	✓	✓	✓	Simulation	BLE, AODV [289]

* not available.

On-Demand Distance Vector (AODV) [289], Dynamic Source Routing (DSR) [290] and the Zone Routing Protocol (ZRP) [278] have the potential to work in Bluetooth scatternets with modifications tailored to the characteristics of Bluetooth technology [183]. Table 7 lists proposed packet forwarding mechanisms for Bluetooth scatternets.

The column “Routing” indicates whether a routing protocol is used or if packets are just forwarded. Furthermore, the column “Reactive” specifies whether the approach is proactive, reactive or hybrid. There are many approaches in literature that combine scatternet formation and packet forwarding [99,159,296,302] and many authors claim that it is desirable to combine these two tasks [44,282,315]. Furthermore, many concepts use restructuring of the scatternet’s topology to optimize routing paths (Location-Aware Routing Protocol (LARP) [298], Location Aware Mobility based routing Protocol (LAMP) [307], Cross-layer Optimized Routing for Bluetooth (CORB) [281], the mechanism presented by Zhang and Riley [159], the approach porposed by Johansson and Carr-Motyckova [305], Relay Reduction and Disjoint Route (RRDR) (also denoted as (LORP)[3]) [198] and MObility based Location Aware Route (MOLAR)/ ROute Maintenance Algorithms (ROMA) [192,193]). Generally, it is widely adopted that cross layer information is viable for packet forwarding in scatternets [135].

The scatternet’s reliability is addressed by 11 of the 39 packet forwarding mechanisms listed in Table 7. Two groups concerning the reliability objectives are identified: the first group indirectly increases the scatternet’s reliability by prolonging the network’s lifetime. The mechanisms by Prabhu and Chokalingam [295], by Zhang and Riley [159], by Johansson and Carr-Motyckova [305], Power-aware AODV (P.A. AODV) [282], **B**LE **S**catternet **B**attery-Aware **R**outing (BSBR) [313] and Cluster-based On-demand Routing Protocol (CORP) [181] belong to this group. The second group explicitly tackles the network connectivity and thus, reliability. The costs of a path will be significantly increased if the received signal strength is below a threshold value in CORB [135]. Consequently, the probability that the path is used is reduced. The approaches RRDR [198] and LAMP [307] create two disjoint paths for any pair of source and destination that are members of different piconets. In MOLAR/ROMA [192,193] the received signal strength is used. If the received signal strength is below a threshold the corresponding link is communicated throughout the network as weak link. Following, the specified mechanisms try to reconstruct the topology. Enhanced MOLAR (E-MOLAR) [311] extends this concept by a mechanism that tries to retain the data of an active traffic flow over a weak link.

Five of the mechanisms listed in Table 7 (Multi-Hop Transfer Service (MHTS) [312], Guo et. al [22], BSBR [313], **A**daptation **L**ayer between **BLE** and **R**PL (ALBER) [12] and CORP [181]) are designed for the usage of BLE. Three of them (mechanism presented by Guo et. al, BSBR and CORP) use a reactive routing approach and exploit the individual characteristics of Bluetooth (piconet structure and established unicast connections) instead of using the shared broadcast channel. The route request messages only need to be

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[3] acronym has no one-to-one meaning.

forwarded to master and bridge nodes and thus, the number of required route request messages can be significantly decreased compared to common wireless ad-hoc networks [181]. The fourth approach proposed by Mikhaylov and Tervonen conceives the multi-hop data transfer as BLE service on top of the Generic ATTribute (GATT) Profile. Their mechanism reactively builds a scatternet route from the source to the destination node [312]. The fifth concept ALBER uses the advertising channels for distributing control information and the BLE data channels for the transmission of data packets. The Routing Protocol for Low power and lossy networks (RPL) [314] is used which relies on a logical topology of a Destination Oriented Directed Acyclic Graph (DODAG). RPL was optimized for networks with traffic flows to one or several distinguished sink nodes represented by the DODAG root node(s). As BLE specific routing metric a link quality estimation based on the Round Trip Time (RTT) of a Logical Link Control and Adaptation Protocol (L2CAP) message is proposed by Lee et al. The presented mechanism provides a complete framework to transmit IPv6 packets via a BLE multi-hop network [208].

Only five of the mechanisms listed in Table 7 propose a proactive routing scheme. These are assumed as sub-optimal choice for Bluetooth scatternets [272]. Reactive strategies are often preferred for wireless ad-hoc networks in general and Bluetooth multi-hop networks in particular [271,316] which is emphasized by Table 7: around 79% of the routing approaches fall in the reactive routing category. But reactive routing techniques also have drawbacks - especially in large and high mobility networks: in large networks the route discovery delay tends to be very high. Furthermore, high node mobility increases the probability for frequent route discovery processes that affect all nodes in the network and drain their power sources. However, hybrid mechanisms seem to be a good choice for Bluetooth scatternets [272,284]. The piconet structure cries out for hybrid mechanisms: a master has connections to all of its active slaves and has the knowledge about all of its slaves [307,310]. Furthermore, slaves are only able to communicate directly with their master(s). Consequently, routing information is necessary in master and bridge nodes solely and it is necessary only to maintain routing information about the master devices in a Bluetooth scatternet [272].

8. Real world scatternet implementations

Bluetooth's scatternet capabilities were advertised for years since the technology's announcement in 1998. But due to the lack of detailed specification there are no commercial products available [131,317]. Instead, the enormous potential of Bluetooth's multi-hop networking features aroused a tremendous research interest. Most of the results obtained were gathered using simulation models solely [131]. Nearly all simulations assume simplified conditions regarding the wireless channel and the physical surroundings [2,131]. E.g. interferences, random errors and signal propagation effects imposed by objects in the environment are not considered. Additionally, an exact and comprehensive model of Bluetooth technology characteristics is needed but nearly impossible to provide in simulations. Constraints given by the hardware used as memory sizes [318], processing power, time required for computations, available energy resources, time synchronization and others affect the behavior of proposed scatternet related mechanisms in real world implementations. Consequently, it will be questionable if several of the proposed mechanisms are executable on real Bluetooth hardware [15]. An additional difficulty is that a substantial amount of research works is not compliant to the Bluetooth specification.

A real world scatternet implementation and deployment is not as straightforward as it sounds [318]. The mere formulation of a scatternet formation mechanism is not enough to establish a scatternet consisting of real Bluetooth devices [15]. Jan Beutel thoroughly described the diversity of possible difficulties in [131]: developed protocols and procedures have to address the effects of a variety of possible errors and non-determinisms through repetitions, retransmissions and fallback solutions. Additionally, they have to handle effects caused by properties individual for Bluetooth technology like the classic Bluetooth technology's inquiry behavior: although in radio range it is possible that the inquiry procedure does not detect all nodes in vicinity. Furthermore, the inquiry procedure can last several seconds. Summarizing, Jan Beutel presented a descriptive depiction: the pseudocode of his scatternet formation algorithm covers 8 lines resulting in 2000 lines of real code accompanied by 2000 lines of additional code required for auxiliary functions (like time methods, connection management, data exchange), error handling and fallback mechanisms. Furthermore, one have to deal with a lot of supplementary issues when building up a network composed of many nodes such as required cables (debugging, power supply), possibly batteries, mountings, housings, installation of updates and debugging of a cooperative system [131].

At the beginning of the Bluetooth era the necessary methods to build up scatternets were not supported by available Bluetooth modules [286,292,325]:

- devices were only able to connect to one master at a time
- devices were only able to maintain one connection
- no master/slave role switch implemented
- no master/slave double role

Consequently, devices were not able to take the bridge role [286]. Table 8 gives an overview of implemented Bluetooth scatternets on real hardware platforms. As indicated by the last column of Table 8 there are early scatternet implementations that apply the dual radio approach to cope with the missing support for bridge nodes. For reason of clarity, Table 8 only lists the most important implementations regarding number of nodes, hardware platforms used and realized concepts. But there are some other early approaches that also apply the dual radio mechanism: [286,292,325]. Furthermore, due to the limitations of early Bluetooth modules [130] there are two implementations - namely TreeNet [130] and Bluepleiades [19] - that only cover single-hop scenarios, i.e. all nodes have to be in range of each other. Columns three and four of Table 8 itemizes the hardware platforms used and details the properties of the Bluetooth modules. Conformity to the respective Bluetooth Core specification is given in brackets. One proposal listed in Table 8 uses BLE (**A**daptation **L**ayer between **BLE** and **R**PL (ALBER) [12]). The column "Bluetooth stack" describes the structure of the Bluetooth software stack used. Some implementations are located directly above the Host Controller Interface (HCI) and thus, do not use a software Bluetooth stack but access the methods provided by the Bluetooth chip directly. But most of the classic Bluetooth real world implementations either use the RFCOMM protocol or the PAN profile. The BLE multi-hop network presented by Lee et al. uses HCI to configure link layer properties and disseminate the neighborhood discovery and route maintenance messages on the broadcast advertising channels whereas data packets are transferred using reliable and robust L2CAP connections [12]. The columns "Formation" and "Routing" specify the implemented scatternet formation and routing mechanisms respectively. Details of individual mechanisms are given in Sections 4 and 7 respectively. Although reactive or hybrid routing strategies should be preferred in Bluetooth scatternets there are five implementations that use a proactive scheme (Leopold et al., Du et al., Liu and Al-Anbuk, Beddernet and ALBER). The predecessor of Beddernet is BEDnet [326]. Nielsen et al. evaluate a proactive and a reactive routing mechanism using their BEDnet. They decided to use a proactive one because of the small network size but they propose to use a reac-

Table 8
Synopsis of real world implementations.

Name	Year	Hardware	Bluetooth Module	Topology	Bluetooth Stack	Formation	Routing	# Nodes	Bridge Role
Leopold et al. [317]	2003	BTnode rev. 2	Ericsson ROK 101007 (BT 1.0)	Tree	Direct access to HCI	Based on Blueroot Grown Bluetrees [91]	BlueTinyDB Routing Tree	n.a.*	✗
TreeNet [130,131]	2004	BTnode rev. 2	Ericsson ROK 101007 (BT 1.0)	Tree	Direct access to HCI	TreeNet	Transparent Bridge Concept	15–30	✓
CORB [133,135,281]	2004	PC + BT modules	Commercially available	n.a.*	L2CAP-PAN-TCP/IP-APP	n.a.*	CORB	8	✗
TreeNet+ [154]	2005	BTnode rev. 3	Zeevo ZV4002 (BT 1.2)	Tree	Direct access to HCI	TreeNet+	Transparent Bridge Concept	71	✓
SHAPER [287]	2005	PC + BT Dongles	3Com + Nortek	minimal	L2CAP-PAN-TCP/IP-APP	SHAPER	Transparent Bridge Concept	3	✓
Nachman et al.[319–321]	2005	Intel Mote	Zeevo TC2001P v1.2	Tree	Direct access to HCI	TSF	Reactive	3 clusters with up to 10 motes	n.a.*
SNR [302]	2006	PC + BT Dongles	CSR (BT 1.1, BT 1.2) + Silicon Wave (BT 1.2)	n.a.*	L2CAP-RFCOMM-APP	Manually	Based on AODV	8	✓
Bluepleiades [19]	2006	PC + BT Dongles	DBT-120 rev. 4 (BT 2.0)	Mesh	n.a.*	Bluepleiades	n.a.*	10	✓
Bluepleiades [19]	2006	BTnode rev. 3	Zeevo ZV4002 (BT 1.2)	Mesh	n.a.*	Bluepleiades	n.a.*	10	✓
Du et al. [322]	2007	Proprietary	CSR BlueCore2 (BT 1.2)	Tree	L2CAP-RFCOMM-APP	Proprietary	Based on DSDV	4	✗
SNP [306]	2007	Proprietary	Zeevo ZV4002 (BT 1.2)	n.a.*	L2CAP-RFCOMM-SPP-APP	SNP	Transparent Bridge Concept	10	✓
Liu and Al-Anbuky [323]	2008	PC + BT Dongles	BT 2.0+EDR	Mesh	L2CAP-RFCOMM-APP	Proprietary	RIP	max. 18	✓
Beddernet [324]	2011	PC + BT Dongles	BT 2.0+EDR	Mesh	L2CAP-RFCOMM-APP	Proprietary	DSDV	max. 6	✓
SFX [179,186]	2011	Proprietary [BlueBear (lesswire AG)]	CSR BlueCore4 (BT 2.1+EDR)	Tree	L2CAP-PAN-TCP/IP-APP	SFX	Transparent Bridge Concept	39	✓
ALBER [12]	2016	Raspberry Pi+BLE chip	BCM4356 (BLE 4.1)	DODAG (Tree)	BLE-L2CAP-6LoWPAN-IPv6	implicit through RPL	RPL	31	✓

* not available.

tive one for larger networks. Furthermore, five real world scatternets just use packet forwarding instead of routing. The topology of four of these five mechanisms is a tree. The one of the remaining scatternet implementation is not given. Only three of the mechanisms listed in Table 8 conduct a reactive routing algorithm. The column "# Nodes" states the number of nodes the deployed network consists of. It is obvious that there are only four real world implementations that are composed of a meaningful number of nodes: TreeNet+ [154], Nachman et al. [319], SFX [179] and ALBER [12]. The TreeNet+ [154] scatternet is the successor of the TreeNet [130] implementation that suffers from the constraints imposed by the early Bluetooth hardware used. The three approaches using classic Bluetooth technology share some properties: first of all they use dedicated embedded hardware which is a precondition to integrate the network in a real world application. Furthermore, all three approaches use a tree topology and packet forwarding or a simple flooding based routing mechanism respectively. The main difference is the Bluetooth stack used: whereas TreeNet+ and the implementation proposed by Nachman et al. directly access the Bluetooth module through HCI the SFX scatternet uses the Radio Frequency COMMunication (RFCOMM) protocol for signaling data and the operating system's standard TCP/IP stack and the Bluetooth PAN Profile for user data. The only real world implementation of a BLE multi-hop network considered here uses a proactive routing approach and IPv6 with the 6LoWPAN [327] adaptation layer for data transport [12].

It is expected that IP based services will be used in Bluetooth multi-hop networks [44,135]. Thus, the utilization of the PAN Profile for classic Bluetooth devices is most sustainable. The application of IPv6 and 6LoWPAN [327] for BLE devices as demonstrated by Lee et al. [12] is a very promising solution with respect to IoT - one of its most popular use cases. One would expect a classic Bluetooth scatternet protocol stack as presented by Fig. 10: the Bluetooth physical and data link layer characteristics provided by the Bluetooth module used.

As stated in Section 6 the inter-piconet scheduling strategy has to be implemented by the Bluetooth controller. The HCI layer specifies the interface between dedicated Bluetooth module and the software Bluetooth stack implemented by the platform's main processor. As emphasized by many researchers the packet forwarding mechanism should be implemented above L2CAP [271,284] and below the common IP layer [44] and thus, should be part of the Bluetooth stack [271,284]. Furthermore, the packet forwarding strategy should be implemented in conjunction with the scatternet formation mechanism [44]. Consequently, for classic Bluetooth the packet forwarding and scatternet formation and maintenance methods should be implemented by the PAN Profile - but they are not. To the present day the PAN Profile specifies mechanisms to transfer IP traffic with the help of the BNEP protocol within a piconet solely [135]. As long as scatternet concepts are not part of the Bluetooth specification packet forwarding [274] and scatternet formation and maintenance approaches have to be implemented on application layer as depicted by Fig. 11. The same applies to BLE scatternets: multi-hop network formation and routing are not part of the BLE specification. The BLE Mesh Profile closes the gap by defining mechanisms to operate an interoperable BLE multi-hop network. A connectionless operation based on flooding using only the three advertising channels was

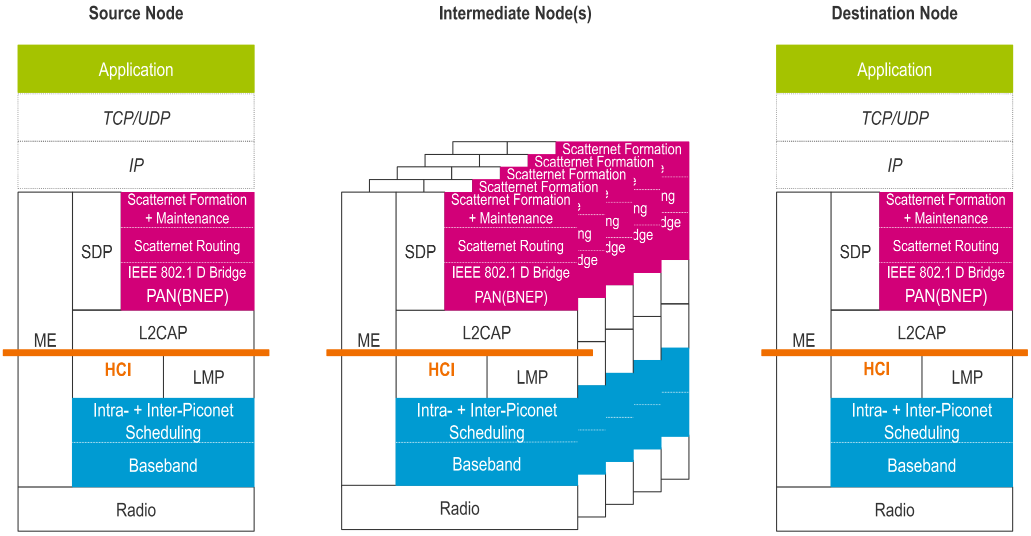

Fig. 10. If the Bluetooth specification defined scatternet concepts the conceptual protocol stack of Bluetooth devices would look like this (assumed that the devices use the PAN Profile). It is optional to use the operating system's default TCP/IP stack therefore, the layers are visualized using dotted lines. This figure is based on the graphics given in the PAN specification [285] and in Huang et al. [135]. The abbreviation ME means Management Entity and LMP denotes the Link Manager Protocol. In this conceptual protocol stack the scatternet routing protocol and rather the scatternet formation protocol have to be part of the PAN Profile. The inter-piconet scheduling strategies have to be implemented by the Bluetooth baseband layer and therefore, they should also be defined by the Bluetooth specification. In a real world implementation the protocol stack will look like presented in Fig. 11 due the lack of scatternet details in the Bluetooth specification.

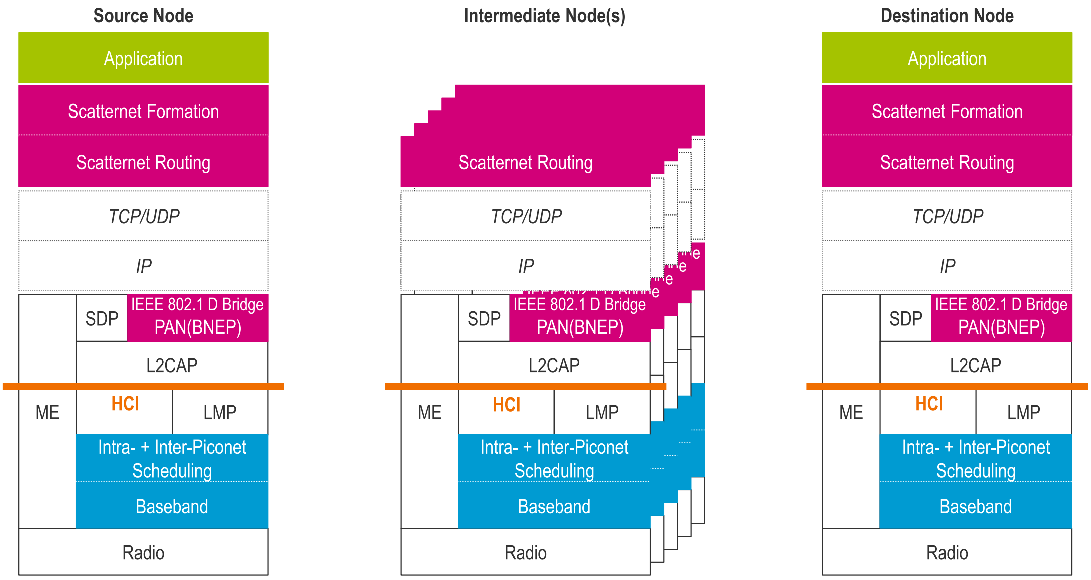

Fig. 11. Protocol stack of Bluetooth devices in a real world scatternet implementation assumed that the devices use the PAN Profile. Based on the graphics given in the PAN specification [285] and in Huang et al. [135]. For real world implementations one has to implement the scatternet formation and routing protocol on application layer - optionally on top of the operating system's default TCP/IP stack. Regarding the inter-piconet scheduling mechanism the user is dependent on the procedures provided by the Bluetooth hardware used.

selected. Consequently, the interference mitigation through FHSS cannot be exploited in BLE Mesh Profile networks because FHSS is used only on data channels. According to Murillo et al. it is application dependent which network type, i.e. connectionless or scatternet, fits best. They compare a connectionless with a scatternet approach. The end to end delay is lower for the connectionless multi-hop network whereas this design option requires a higher energy consumption. The throughput can be considered as comparable. The formation and maintenance of a connected topology cause overhead traffic and take some time. Unfortunately, Murillo et al. do not use the BLE Mesh Profile concepts as reference but another mechanism developed before the BLE Mesh Profile was published [328]. Consequently, their study cannot evaluate the design concepts explicitly integrated to the BLE Mesh Profile to optimize the message flooding and reduce the energy demand, i.e. Heartbeats, TTL, the message cache and the Friend feature.

Bluetooth's multi-hop ad-hoc networking capabilities sound promising but their implementation on real world hardware platforms given that the BLE Mesh Profile does not satisfy application needs is difficult as long as required concepts and methods are not part of the Bluetooth specification. Furthermore, the diversity of hardware platforms used and a lack of a common agreement about nodes' capabilities complicate the development of consistent strategies [115]. Nevertheless, there seem to be commercial products using proprietary solutions of Bluetooth scatternets [329] but neither conceptual details nor performance measurements are accessible.

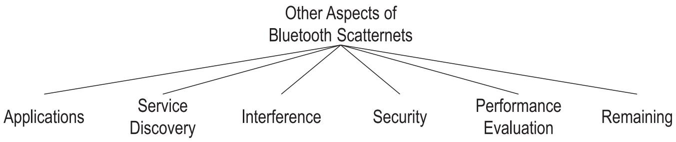

Fig. 12. Further Bluetooth scatternet related topics discussed in literature.

9. Other aspects of Bluetooth multi-hop networks

For the sake of completeness this section shortly presents some other topics discussed in literature in conjunction with Bluetooth multi-hop networks. The aspects include applications, service discovery issues in Bluetooth multi-hop networks, interference mitigation in Bluetooth multi-hop networks, security facets, performance evaluation and some remaining works covering particular topics (cf. Fig. 12). Some application proposals depending on a Bluetooth scatternet are described conceptually and assume the existence of a connected scatternet like [330]. Several other publications use simulations to evaluate their proposed application ([331–335]) and a few are based on a real world implementation ([263,336–339]). Martínez et al. present a real world application based on a BLE Mesh Profile network [340]. Bluetooth's Service Discovery Protocol (SDP) only works for piconet structures and thus, in a Bluetooth multi-hop network similar procedures are needed. A proposal for the extension of SDP in a scatternet is given in [341]. A scatternet consists of several piconets that partially overlap and in a BLE Mesh Profile network the node density can be very high. Some works address the interference imposed by overlapping piconets or dense node deployments and suggest mechanisms to reduce the consequences of such interferences ([342–345]). Different facets of scatternet security issues are discussed in the literature. Extensions of Bluetooth's security mechanisms tailored for the scatternet scenario are presented in [346]. Scatternet formation mechanisms designed with security in mind are presented in [286,347,348]. A key distribution approach is described in [349] and application layer security mechanisms for authentication and message integrity in Bluetooth scatternets are introduced in [350,351]. Approaches to determine the resulting performance of different scatternet design choices like topology, device roles etc. are presented in [352,353] and [354]. Murillo et al. present an automated testbed capable to compare different mesh protocols on top of BLE. The testbed can be used free of charge by everybody. They compare a connectionless flooding based mesh protocol developed before the BLE Mesh Profile has emerged with the open-source BLE scatternet FruityMesh [180] and conclude that both approaches can be a good choice depending on the application's needs [328].

10. Conclusion

Billions of Bluetooth devices are scattered around the world. Thus, the potential of building ad-hoc multi-hop networks is promising which triggered an enormous research interest in Bluetooth multi-hop networks throughout the last 20 years. This paper surveys the tremendous work done on Bluetooth multi-hop networks by analyzing over 400 research papers. To the best of the authors knowledge this is the first survey summarizing the key findings of the last 20 years for classic Bluetooth technology as well as Bluetooth Low Energy, including the Bluetooth Low Energy Mesh Profile.

The evaluation of the sub-topic(s) discussed in each work considered leads to the structure of this survey paper. At the beginning the fundamental basics of Bluetooth technology are figured out followed by a section introducing the main characteristics of the Bluetooth Low Energy Mesh Profile. Generally, two types of Bluetooth multi-hop networks are identified: connected networks (scatternets) and connectionless networks relying on message broadcasting. The main sub-topics discussed throughout the last 20 years are scatternet formation and topology maintenance and optimization, inter-piconet scheduling and packet forwarding. Each of these topics is reviewed in an individual section. The distinct feature of this survey is the classification of the most relevant works on each topic in a single tabular form considering the key properties solely. The intention is to provide a clear overview of existing approaches and achievements with a spotlight on real world feasibility. Details of single works are only mentioned to highlight the overall development progress in each field or to discuss properties essential for a real world implementation. The focus on technical feasibility is stressed by a particular section reviewing real world implementation efforts. Both types of Bluetooth multi-hop networks have their right to exist supporting distinct applications. Although connected Bluetooth multi-hop networks are not standardized several works demonstrated their technical feasibility. Methfessel et al. even managed to operate a connected Bluetooth multi-hop network in a photovoltaic power plant.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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