

Low Energy Bluetooth

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Abstract-

Bluetooth Low Energy (BLE) is partner climbing low-control remote engineering created for short-run administration and perception applications that is required to be joined into billions of gadgets inside the following few years. This paper portrays the most alternatives of BLE, investigates its potential applications, and researches the effect of differed vital parameters on its execution. BLE speaks to an exchange off between vitality utilization, inactivity, piconet size, and throughput that chiefly relies on upon parameters like curl interim and con Slave Latency. In keeping with hypothetical comes about, the time of a BLE gadget steam-fueled by a coin cell battery goes between two.0 days and fourteen.1 years. The amount of concurrent slaves for every expert ranges somewhere around two and five, 917. The base dormancy for an expert to get an indicator perusing is 676 μ s, however reproduction results demonstrate that, underneath high bit blunder rate, normal inactivity will increment by up to a couple of requests of size. The paper gives exploratory comes about that supplement the hypothetical and reenactment discoveries, and shows execution requirements that will curtail BLE execution.

Keywords:

Bluetooth Low Energy; Sensor Networks; Internet of Things

I. Introduction

Bluetooth Low Energy (BLE) is Associate in Nursing rising wireless technology developed

by the Bluetooth interest group cluster (SIG) for short-range communication. In distinction with

previous Bluetooth flavors, BLE has been designed as a low power resolution for management and observation applications. BLE is the grandeur of the Bluetooth four.0 specification. The arrival of BLE has occurred whereas different low powered wireless solutions like zig bee, 6LoWPAN or Z -Wave are steady gaining momentum in application domains that multi hop networking. However, BLE constitutes a single hop resolution applicable to a unique area of use cases in areas like aid, shopper physical science, sensible energy and security. The widespread use of Bluetooth technology (e.g., in mobile phones, laptops, cars, etc.) could fuel adoption of BLE, since implementation of the latter will leverage similarities with classic Bluetooth. In line with printed forecasts, BLE is predicted to be utilized in billions of devices within the close to future. In fact, the IETF 6LoWPAN unit (WG) has already recognized the importance of BLE for the net of Things. As of the writing of this text, the 6LoWPAN WG is developing a specification for the transmission of IPv6 packets over BLE. This paper describes the most options of BLE, investigates the impact of important parameters on its performance, and explores its potential applications. the remainder of the paper is organized as follows: Section a pair of overviews the BLE protocol stack and describes the operation and main characteristics of every layer; Section three evaluates the energy consumption, latency and network size of BLE and discusses application layer BLE throughput; Section four

explores the applying and market adoption potentialities for BLE, and provides a comparison with different wireless low-power technologies. Finally Section five concludes the paper with the most remarks.

II. Bluetooth low energy protocol stack

This section presents the BLE protocol stack, and describes the main mechanisms and features of each layer.

A. BLE protocol stack overview

Like in classic Bluetooth, the BLE protocol stack consists of 2 main parts: the Controller and therefore the Host. The Controller includes the Physical Layer and therefore the Link Layer, and is usually enforced as a little System-on-Chip (SOC) with an integrated radio. The Host runs on an application processor and includes higher layer practicality, i.e., the Logical Link management and Adaptation Protocol (L2CAP), the Attribute Protocol (ATT), the Generic Attribute Profile (GATT), the safety Manager Protocol (SMP) and therefore the Generic Access Profile (GAP). Communication between the Host and therefore the Controller is standardized because the Host Controller Interface (HCI). Finally, non-core profiles (i.e., application layer practicality not outlined by the Bluetooth specification) will be used on prime of the Host. Figure 1(a) illustrates the BLE protocol stack. Figure 1(b) depicts the structure and size of the various fields contributed by every layer to a Physical Layer information unit once application information is transmitted. Though a number of BLE controller options are transmissible from the classic Bluetooth controller, each form of controller is presently incompatible. Hence, a tool that solely implements BLE cannot communicate with a tool that solely implements classic Bluetooth. It's expected that several devices can implement

each the classic Bluetooth and therefore BLE protocol stacks. These devices are known as dual mode devices.

B. Physical layer

BLE operates within the two.4 Gc Industrial Scientific Medical (ISM) band and defines four frequency RF channels with two megacycles per second channel spacing. These area units 2 kinds of BLE RF channels: advertising channels and knowledge channels. Advertising channels area unit used for device discovery, affiliation institution and broadcast transmission, whereas knowledge channels are unit used for bidirectional communication between connected devices, 3 channels area unit outlined as advertising channels. These channels are assigned center frequencies that minimize overlapping with IEEE 802.11 channels one, 6 and 11, that area unit ordinarily utilized in many countries. Associate adaptive frequency hopping mechanism is employed on high of the info channels so as to face interference and wireless propagation problems, like weakening and multipath. This mechanism selects one among the thirty seven on the market knowledge channels for communication throughout a given interval. All physical channels use a mathematician Frequency Shift Keying (GFSK) modulation that is easy to implement. The modulation index is within between zero.45 and 0.55 that permits reduced peak power consumption. The physical layer rate is one Mbps. The receiver sensitivity is outlined in BLE because the amplitude at the receiver that to a small degree Error Rate (BER) of 10^{-3} is achieved. The BLE specification mandates sensitivity higher than or adequate to -70 dBm. The coverage vary is usually over varied tens of meters.

C. Link layer

In BLE, once a tool solely must broadcast knowledge; it transmits the info in advertising packets through the advertising channels. Any device that transmits advertising packets is termed advertiser. The transmission of packets through the advertising channels takes place in intervals of your time known as advertising events. Inside advertiser advertising event, the advertiser consecutively uses every advertising channel for packet transmission. Devices that solely aim at receiving knowledge through the advertising channels area unit known as scanners. Bidirectional electronic communication between 2 devices needs them to attach to every alternative. The creation of an affiliation between 2 devices is associate uneven procedure by that advertiser announces through the advertising channels that it's a connectable device, whereas the opposite device (referred to as associate initiator) listens for such advertisements. Once advertiser finds associate advertiser, it's going to transmit an affiliation Request message to the advertiser, which creates a point-to-point affiliation between the 2 devices. Each device will then communicate by exploitation the physical knowledge channels. The packets for this affiliation are known by random generated 32-bit access code. BLE defines 2 device roles at the Link Layer for a created connection: the master and therefore the slave. These area unit the devices that act as leader and advertiser throughout the affiliation creation, severally.

D. L2CAP

The L2CAP utilized in BLE is associate optimized and simplified protocol supported the classic Bluetooth L2CAP. In BLE, the most goal of L2CAP is to multiplex the info of 3 higher layer protocols;

ATT, SMP and Link Layer management communication, on high of a Link Layer affiliation. The info of those services area unit handled by L2CAP in a very best-effort approach and while not the employment of retransmission and flow management mechanisms, that area unit on the market in alternative Bluetooth versions. Segmentation and refabrication capabilities don't seem to be used, since higher layer protocols give knowledge units that match into the utmost L2CAP payload size that is adequate to twenty three bytes in BLE.

E. ATT

The ATT defines the communication between 2 devices taking part in the roles of server and shopper, severally, on high of a fervent L2CAP channel. The server maintains a group of attributes. Associate attribute could be a system that stores the data managed by the United Nations agency, the protocol that operates on high of the ATT. This hopper or server role is decided by the United Nations agency, and is freelance of the slave or master role. The shopper will access the server's attributes by causing requests that trigger response messages from the server. For larger potency, a server also can send to a shopper 2 kinds of uninvited messages that contain attributes: (i) notifications, that area unit unconfirmed; and (ii) indications, that need the shopper to send a confirmation. A shopper might also send commands to the server so as to write down attribute values. Request/response and indication/confirmation transactions follow a stop-and-wait theme.

F. GATT

The GATT defines a framework that uses the ATT for the invention of services, and therefore the exchange of characteristics from one device to a different. A characteristic could be a set of knowledge which has a worth and

properties. The info associated with services and characteristics area unit hold on in attributes. For instance, a server that runs a “temperature device” service could account with a “temperature” characteristic that uses associate attribute for describing the sensor, another attribute for storing temperature measure values and an additional attribute for specifying the measure units.

G. Security

BLE offers varied security services for shielding the data exchange between 2connected devices. Most of the supported security services may be expressed in terms of 2 mutually-exclusive security modes known as lupus security mode one and lupus security mode two. These 2modes give security practicality at the Link Layer and at the ATT layer, severally. The BLE Link Layer supports coding and authentication by exploitation the Cipher Block Chaining-Message Authentication Code (CCM) formula and a 128-bit AES block cipher. Once coding and authentication area unit utilized in an affiliation, a 4-byte Message Integrity Check (MIC) is appended to the payload of the info channel PDU. Encryption is then applied to the PDU payload and MIC fields. It’s additionally attainable to transmit echo over associate unencrypted Link Layer affiliation. During this case, a 12-byte signature is placed when the info payload at the ATT layer. The signature is computed by applying associate formula that uses 128-bit AES because the block ciphers. One input to the formula could be a counter that is employed so as to produce protection against replay attacks. If the receiver verifies the signature, it assumes that the info is sent by the trustworthy supply. Additionally to the delineated services, BLE supports a mechanism known as privacy feature, that permits a tool to use personal addresses and

often modification them. The privacy feature mitigates the threat by that associate individual will track a BLE device.

H. Gap and application profiles

At the very best level of the core BLE stack, the GAP specifies device roles, modes and procedures for the invention of devices and services, the management of association institution and security. The BLE GAP defines four roles with specific necessities on the underlying controller: Broadcaster, Observer, Peripheral and Central. a tool within the Broadcaster role solely broadcasts information (via the advertising channels) and doesn’t support connections with different devices. The Observer role is complementary for the Broadcaster, i.e., it’s the aim of receiving the info transmitted by the Broadcaster. The Central role is intended for a tool that’s accountable of initiating and managing multiple connections, whereas the Peripheral role is intended for easy devices that use one reference to a tool within the Central role. In consequence, the Central and Peripheral roles need that the device’s controller supports the master and slave roles, severally. a tool might support numerous roles, however only 1 role are often adopted at a given time. Finally, since sure kinds of applications might like reusing common practicality, further profiles are often designed on high of the GAP. Bluetooth follows a profile hierarchy, whereby a brand new profile as well as all the necessities of Associate in nursing existing profile is often outlined.

III. Performance analysis

This section evaluates the performance of BLE in terms of energy consumption, latency and piconet size, for numerous use cases and configurations, and discusses application layer BLE outturn. the dimensions of the notification,

command and response messages thought-about during this study is that the most one (i.e., thirty seven bytes at the Physical Layer), whereas polls sent by the master and acknowledgments area unit assumed to be empty PDUs (i.e., PDUs while not payload). Latency results are obtained by exploiting simulation tools that we have a tendency to developed for this purpose (given that current simulators don't support BLE yet), and are complemented by suggests that of experimental measurements. The simulation tools model 2connected BLE devices that communicate with one another, taking into consideration all the BLE stack layers and their behavior within the presence of bit errors. Piconet size results are obtained in theory, whereas energy consumption has been analyzed each in theory and through empirical observation.

A. Energy consumption

We have a tendency to 1st investigate the theoretical time period of a slave that's connected to a master in a very information assortment application. Note that a slave is often a tool with restricted energy provide, whereas a master might not suffer an equivalent energy constraints. we have a tendency to take into account two totally different strategies by that the master obtains detector measuring readings (which area unit handled as attribute values) from the slave, that is assumed to act. We have a tendency to denote these strategies by unidirectional ATT communication and round-trip ATT dialogue, severally. Within the unidirectional ATT communication, the slave sends a notification in response to a poll from the master. Within the round-trip ATT dialogue, the master sends missive of invitation to the slave, that transmits a response to the master (and each the request and also the

response trigger Link Layer acknowledgments). For the 2 strategies delineated, the primary packet transmission from the master takes place at the start of every association event. The analysis is dispensed in theory by forward current consumption values obtained from measurements for the CC2540 radio chip, for a transmit power of zero dBm. Specifically, for the unidirectional ATT communication, the study takes into consideration the energy consumed throughout all of the subsequent states: device rouse, radio activate (in order to receive the initial BLE packet from the master), request reception, radio switch to transmit mode, notification transmission, and post-processing before the device returns to sleep mode. For the round-trip ATT dialogue, the extra energy consumption because of response transmission, radio switch to receive mode, and acknowledgment reception is additionally thought-about. The energy consumption throughout sleep periods is taken into account furthermore for each kind of ATT transactions. For the analysis of the device time period, we have a tendency to assume a perfect battery with a capability of 230 mAh (i.e., a typical price for a coin cell battery). The study considers the impact of Interval and Slave Latency parameters. the total vary of valid connInterval values (i.e., from 7.5 ms to 4000 ms) is roofed. For connSlaveLatency, values within zero and seven area unit thought-about, since these values are often used for any allowable conn Supervision Timeout setting. The study is additionally dispensed for the most attainable Slave Latency price, that is given for the most common Super vision Timeout price, and depends on the Interval price. For this study, a BER adequate to zero is assumed, which supplies Associate in Nursing boundary on the slave time period underneath the delineated conditions. the most slave time period obtained isfourteen.1 and

12.4 years for the unidirectional and round-trip strategies, severally.

B. Latency

we have a tendency to next study by simulation the common latency of unidirectional ATT communications and round-trip ATT dialogues between a master and a slave, as a perform of the Interval parameter, and for numerous BER values. samples of the one- means ATT communications thought-about embody the following: (i) the master polls the slave and also the slave replies with a notification or a command; (ii) the master sends a notification or a command, and also the slave acknowledges the master's

message at the Link Layer. The round-trip ATT dialogue thought-about is that the same as that assumed within the energy consumption analysis. The latency of every message exchange is measured because the distinction of times between the beginning of the transmission of the primary message and also the finish of the proper reception of the last message. we have a tendency to assume that a association has been created between the 2 BLE devices before the ATT message exchange. Figure half dozen illustrates the results, that area unit obtained because the average latency from 10 million simulated message exchanges for every set of conditions. A Slave Latency adequate to zero is assumed. The results don't embody the latency for the primary packet of the association. In fact, the master has flexibility in choosing the beginning time of the primary packet transmission, which may occur between one.25 ms and eleven.25 + Intervals when the transmission of the association Request message.

For terribly low BER values, the common latency of round-trip and unidirectional ATT message exchanges

area unit smaller than a pair of ms and one ms, severally, for any connInterval price. However, for larger BER values, the influence of connInterval becomes important, since on the average over one association event is needed for no-hit transmission of every ATT message

C. Maximum piconet size

We tend to next investigate the utmost piconet size, i.e., the utmost variety of slaves that a master will handle. In BLE, every affiliation between a master and a slave is known by a 32-bit access address. on the far side this truth, the Bluetooth four.0 specification doesn't impose additional limits on the quantity of slaves that may be connected to a master. However, there exist sensible limits on its variety, reckoning on the kind of communication between master and slave, on the connInterval parameter setting and therefore the BER that may be assumed. the utmost piconet size is freelance of the connSlave Latency parameter, as a result of the inactive affiliation events thanks to slave latency can't be used for connections with alternative slaves. Figure eight depicts the theoretical most variety of slaves that a master will handle for varied configurations. This variety is evaluated for the unidirectional and round-trip ATT interactions thought-about within the latency study. Associate bound on the utmost variety of slaves per master is obtained by considering ideal communications (i.e., BER = 0). Additionally, a secure planning theme has been evaluated, whereby the communications between a master and 2 totally different slaves cannot overlap even once bit errors result in retransmissions. Theoretical most variety of slaves per piconet for varied forms of interactions between devices and planning schemes. The quantity of slaves that a master will handle

varies considerably reckoning on the setting of the `connInterval` parameter..

D. Throughput

The utmost BLE application layer output for a affiliation between 2 devices has been obtained in previous work by simulation and mathematical analysis, as a operate of `connInterval` and BER [13]. Whereas the physical layer rate is one Mbps, the utmost application

layer output is adequate 236.7 kbps. On the opposite hand, recall that if associate of {the 2} connected devices receives two consecutive packets with an invalid CRC check, the affiliation event ends. Thus, the transmission of knowledge can't be resumed till the start of subsequent affiliation event, whereby a replacement information channel (i.e., a replacement frequency) is employed. This behavior prevents any surplus waste of energy whereas bit errors square measure being found in one information channel. However, this theme degrades the effective output of BLE within the presence of bit errors. In such conditions, moderate to high output will solely be achieved for terribly low `connInterval` values. Despite the theoretical or simulation-primarily based findings, the utmost BLE output that may be achieved in a very real state of affairs could also be restricted thanks to a range of things. These embrace implementation constraints like the quantity of application layer messages a tool will send per affiliation event (due to memory limitations), yet as process delays. We've got conducted experiments so as to live the utmost realizable output in a very BLE link composed of 2 connected CC2540 devices. the gap between each devices is zero.5 m and their transmit power is zero dBm. in step with our measurements, in these conditions, the BER of the BLE link is below 10⁻⁵. In every experiment, the slave has been

programmed to send the utmost variety of notifications allowed by the BLE stack presently employed in the CC2540 (i.e., four notifications per affiliation interval). consequently, we've got set `connInterval` and `connSlave Latency` to the tiniest attainable values (i.e., 7.5 ms and 0, respectively). every notification has the utmost size (i.e., twenty bytes of application layer payload). The experiment is disbursed for a thousand affiliation events. within the delineated conditions, the utmost application layer output we've got measured is fifty eight.48 kbps. This low result will be explained by the subsequent 2 facts: (i) whereas, in theory, up to eleven such notifications will be transmitted at intervals a affiliation event of seven.5 ms, solely four notifications square measure allowed per affiliation event, as aforementioned; and (ii) we've got discovered that but four notifications are literally transmitted in most affiliation events throughout the experiment (however, identical development happens less often for affiliation intervals bigger than seven.5 ms). These observations show that top output has not been a primary goal within the style of the BLE implementation employed in the analysis.

IV Applications and market adoption

BLE could like the widespread use of Bluetooth technology, since BLE simply integrates into classic Bluetooth electronic equipment, and therefore it's doubtless that future Bluetooth devices are going to be dual-mode devices in step with printed forecasts, BLE is predicted to be employed in billions of devices within the close to future. Seeable of the necessary role that BLE could play within the web of Things, the IETF 6LoWPAN WG is developing a specification so as to change end-to-end information science communications for BLE devices. for instance, BLE-equipped sensible phones will act as information science routers

for BLE-enabled sensors and actuators. Information science property could dramatically increase the potential house of services and value-added price for BLE devices. Whereas BLE is rising, alternative low-power wireless technologies, like Zig Bee, 6LoWPAN or Z-Wave, have already achieved vital presence in many market segments. However, they are doing not have high preparation expectations in devices like sensible phones. BLE, on the opposite hand, is predicted to own a powerful position in these. Table a pair of shows the most characteristics of BLE and therefore the said technologies (classic Bluetooth has been enclosed for comparison purposes).

Conclusion

This paper describes the BLE protocol stack, provides a performance analysis of this technology and explores its potential applications. In BLE, there exists a trade-off between energy consumption, latency, piconet size, and output that in the main depends on the Conn Interval and Slave Latency parameters. Analysis results show however these parameters may be tuned showing wisdom so as to satisfy application necessities. On the opposite hand, the paper points out many implementation constraints which will cut back BLE performance in a very real situation, as compared with the on paper expected one. BLE emerges as a robust low-power wireless technology for single-hop communication use cases which can contribute to connecting a dramatically great amount of recent devices to the web of Things.

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