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Throughput Characterization for Bluetooth Low Energy with Applications in Body Area Networks

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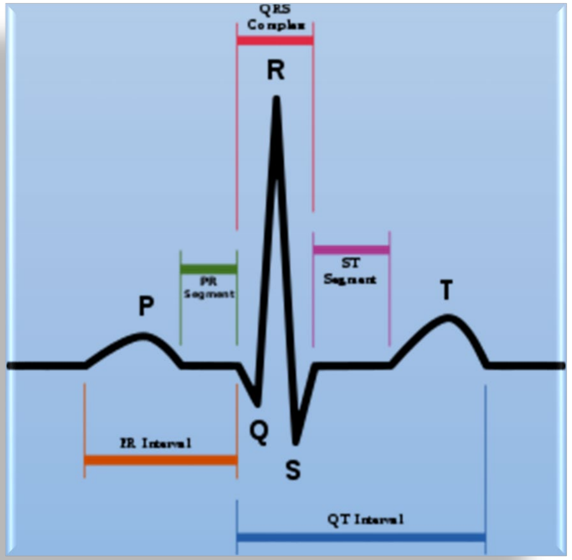
Motivation and Scope

- Bluetooth Low Energy (BLE) has emerged as a technology of choice in many applications including body area networks (BAN).
- This work investigate the use of BLE in terms of throughput, power consumption and latency and evaluate its suitability for BAN applications.
- Compare the performance of different versions of the Bluetooth core specification using a theoretical model and an experimental setup based on nRF52840 chip by Nordic Semiconductor
- Conclude with a case study of Electrocardiography (EKG) and provide the current consumption and battery lifetime estimation of an EKG BLE node for different BLE versions and configurations.

EKG as a Case Study

- Goal is to evaluate the use of BLE in the context of BAN applications that require continuous data streaming with steady throughput and low latency. EKG as an ideal example of such applications.



- The EKG signal is a representation of the heart muscle activity with bandwidth 0.05-100 Hz.
  - The heart rate sampling frequency is typically chosen between 250 Hz and 500 Hz or higher.
  - EKG values are commonly represented using 15-16 bits per sample.
  - Low power consumption for the EKG sensor is an essential requirement to achieve a convenient duration of sensor's lifetime.

BLE Versions

Core Specification version	Publication Date	Main Changes
4.0	Jun 2010	BLE was first adopted.
4.1	Dec 2013	Adding simultaneous multi-role support: a device can simultaneously be advertising, scanning, connected as a slave and/or a master, or any subset of these states.
4.2	Dec 2014	- Adding ECDH security pairing. - Adding length extension feature: maximum length of a LL packet payload on a data channel increased to 251 bytes. - Enhancing privacy: hiding the public BLE address to prevent tracking.
5	Dec 2016	- Adding optional 2 Mbps PHY (doubling speed). - Adding optional coded 1 Mbps with correction coding rates 1/2 and 1/8, thus quadrupling the communication range. - Adding advertising enhancements and packet length extension.

Brief Overview of BLE Communication Protocol

- On the Generic Attribute Profile (GATT) level, two roles are defined (Server and Client):
  - A server may initiate the delivery of the value of a certain characteristic (for example, a sensor's reading) to the client using one of two GATT procedures,
    - Notifications or Indications. An indication requires a response on the GATT level, while a notification does not require a GATT-level response.
- The GATT payload is transmitted over Attribute (ATT) Protocol Data Units (PDU) whose maximum allowable size is called the Maximum Transfer Unit (MTU) size, and is implementation-specific with a minimum of 23 bytes.
- The notification ATT PDU is carried over a logical Layer Control and Adaptation (L2CAP PDU).
  - If the length of the L2CAP PDU is equal to or smaller than the maximum LL data length, the whole L2CAP PDU is transmitted in one LL PDU. Otherwise, the L2CAP PDU is fragmented over more than one LL PDU.

BLE Throughput Calculations

- Consider a GATT notification packet that carries L_{char} bytes of a characteristic value. Taking into consideration the notification ATT PDU and L2CAP PDU overheads, the L2CAP PDU length of such notification packet is $L_{L2CAP} = (L_{char} + 7)$ bytes.
- Consider the simple case when the L2CAP PDU fits in one LL PDU i.e. L_{L2CAP} is less than or equal to maximum LL data length. Let L_S and L_C be the total LL packet length in bytes of the server's packet and the client's packet respectively, then

$$L_S = L_{L2CAP} + \text{LL overhead} \qquad L_C = \text{LL overhead}$$

- where LL overhead is 10 bytes for LE 1M and 11 bytes for LE 2M and the client's packet has zero-length LL payload.
- The time interval $T_{exchange}$ that is required for one packet exchange is given by

$$T_{exchange} = \frac{(L_S + L_C) * 8}{R} + (2 * IFS)$$

- where R is the PHY rate and IFS is the inter-frame spacing between two successive LL packets and is equal to 150 µs.

BLE Throughput Calculations

- An upper bound for the application throughput can be easily derived, assuming continuous transmission of packet exchanges, as follows:

$$\text{Throughput upper bound} = \frac{L_{char} * 8}{T_{exchange}}$$

- To achieve this upper bound, the used connection interval value *CI* must be an integer multiple of $T_{exchange}$, and the chip must support sending up to (CI / $T_{exchange}$) packet exchanges per connection event. In the absence of packet errors, the actual throughput can be calculated as

$$\text{Throughput} = \frac{L_{char} * 8 * PPCE}{CI}$$

- where *PPCE* is the number of packet exchanges per connection event that the chip can transmit when a connection interval of *CI* is used and each packet exchange takes $T_{exchange}$ seconds. *PPCE* is an integer that is upper-bounded by the value ($CI/T_{exchange}$) that denotes the continuous transmission case.

BLE Throughput Calculations (Fragmentation Across Multiple LL)

- Similar analysis can be done for the case when the L2CAP PDU is fragmented across more than one LL PDU.
  - LL PDUs may not be equal in length and therefore the amount of transmitted bytes may differ from one connection event to another.
  - The average throughput can still be calculated using a modified version of the previous equations as follows. If the L2CAP PDU is fragmented over N LL packets, such that

$$N = \left\lceil \frac{L_{L2CAP}}{\text{max LL data length}} \right\rceil$$

- A local maximum throughput value occurs whenever L_{L2CAP} is a multiple of the max LL data length, because this ensures the usage of maximal-length LL PDUs and thus minimizes the ratio of the LL overhead to the payload size.

Experimental Setup

- Platform: nRF52840 preview development kit by Nordic Semiconductor:
  - nRF52840 System-on-Chip (SoC) supporting BLE 5.
  - On the peripheral, we implemented a proprietary characteristic with configurable length. This characteristic is notified periodically with configurable time interval between successive notifications. Notification packets are queued till the next connection event, when they have the opportunity to be sent. Therefore, the choice of the connection interval controls the delay introduced by the wireless protocol.
- Measurment Scenarios:
  - MTU size is set to 247 bytes and Lchar is 244 bytes.
    - Values correspond to the highest value of MTU size that can be transported over one LL PDU, if the LL data length is set to its maximum value of 251 bytes.
    - Nodes are placed close to each other such that channel conditions are excellent and packet error rate is negligible.
    - Current consumption is measured by the power profiler kit from Nordic Semiconductor. The average current over one minute of measurement is recorded for every case.

Measured Throughput vs. Manufacturer vs. Theoretical maximum.

PHY	CI (ms)	Max LL length (bytes)	Measured throughput (kbps)	Reported throughput (kbps)	Max throughput (kbps)
1M	50	27	286.6	N/A	295.4
1M	400	27	281.2	N/A	
1M	50	251	743.9	702.8	790.9
1M	400	251	758.7	771.1	
2M	50	251	1326.2	1327.5	1402.3
2M	400	251	1317.3	1376.2	

- The difference between the measured throughput results and the values reported by the manufacturer is less than 6%.
- Measurements achieve 94-97% of the throughput upper bound.
- Throughput varies when *CI* is changed because an integer number of LL packet exchanges should fit within the connection event for each value of *CI*.

Impact of LL Packet Length

- The application throughput depends on the relation between the ATT PDU size and maximum LL data length.
    - When the maximum LL data length is 27 bytes, the last LL packet of every fragmented L2CAP packet will not be of maximal LL length.
    - An upper bound of LL throughput that is independent of the choice of *CI* can be calculated by using the maximum LL data length instead of L_{char}. The first BLE version that supports the chosen parameters is given in each case.
- This shows that the LL throughput has increased by about 155% by increasing the LL data length from 27 bytes to 251 bytes, and by about 77% by doubling the PHY rate.

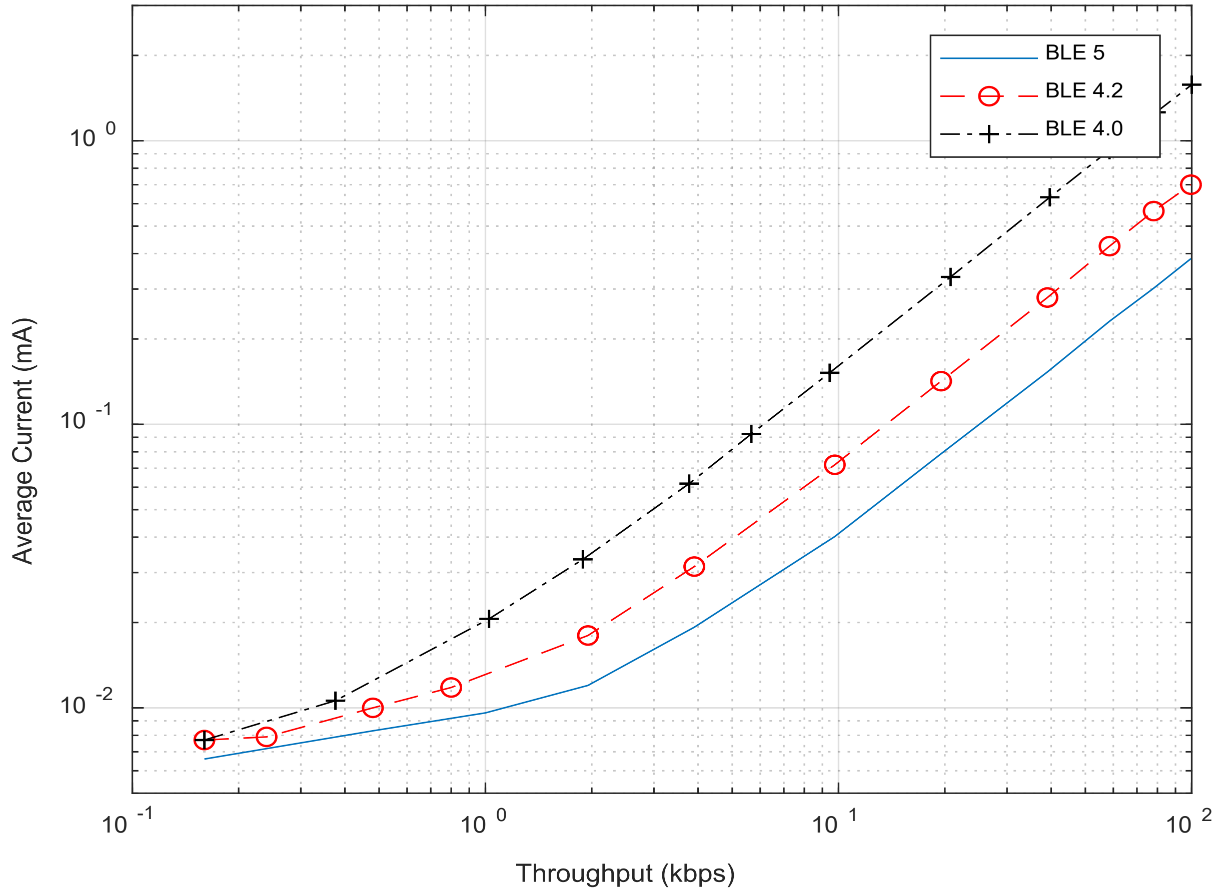
BLE version	PHY	Max LL data length (bytes)	LL throughput upper-bound (kbps)
4.0	1M	27	319.5
4.2	1M	251	813.6
5	2M	251	1442.5

Current Measurement Procedure

- Processor wakes up at the desired rate and logs data of the specified size each time.
- Readings are aggregated in notification PDUs and sent in the next available connection event.
  - The sensor current is not considered in the power consumption. To get an estimate of the overall current consumption of the system, the sensor current as given by the sensor's specification is accounted for.
  - Current consumption for throughput values up to 100 kbps is investigated, which is the typical range for medical streaming applications.

Current Measurement Results

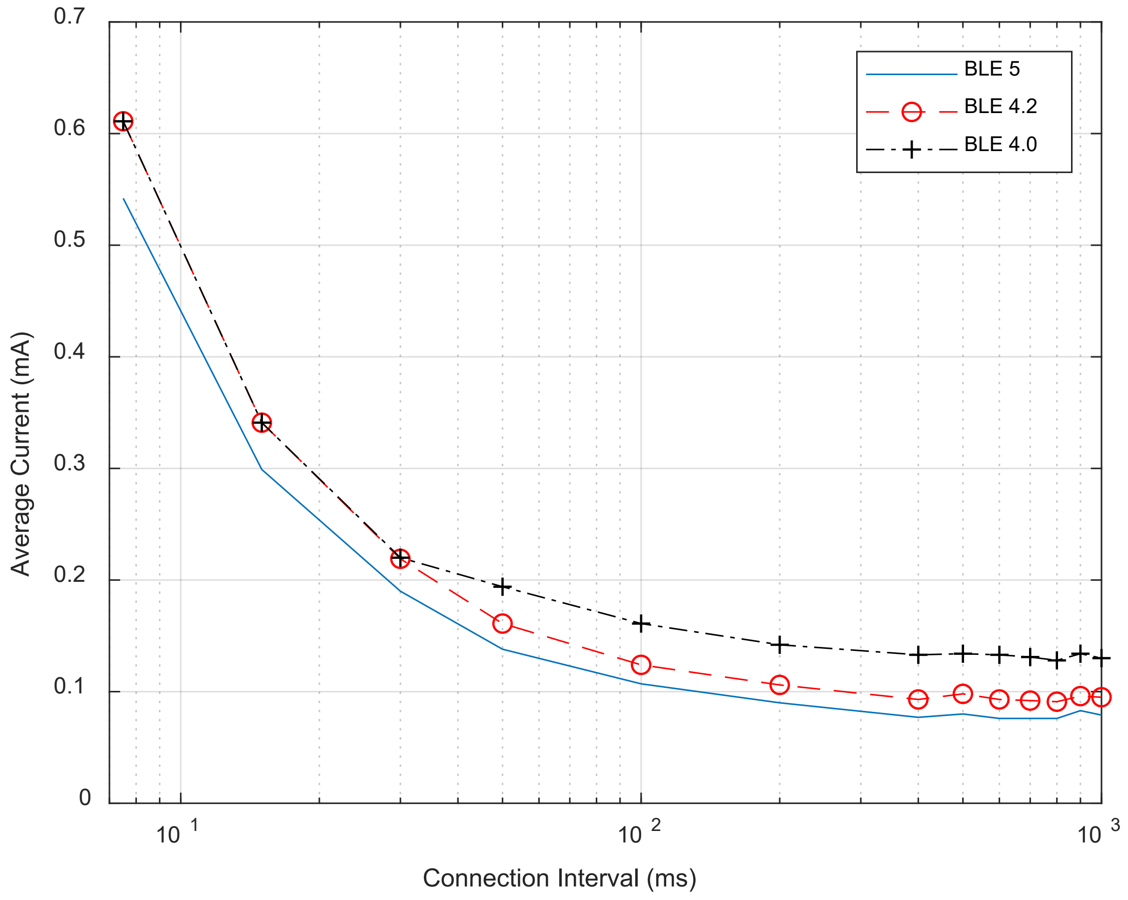
- For Tx rates > 2kbps total power consumption is dominated by the radio transmission power which is proportional to the throughput.
- There is an average reduction of 55% of power consumption when the LL data length is extended from 27 bytes to 251 bytes.
- Another 40% of power reduction comes when LE 2M is used, compared to LE 1M.
- The tradeoff of the increased packet length is the increase in the probability of packet errors and collisions.
- With uncoded PHYs, a packet that encounters an error has to be retransmitted. The extra cost of LE 2M is the increased signal bandwidth.



Current consumption versus throughput for *CI* = 1 s and transmit power = 0 dBm

EKG Current Measurement Results

- Processor logs a 16-bit data field demonstrating an EKG reading, with a frequency of 300 samples per second, thus the required throughput is 4.8 kbps.
- Readings are aggregated into one characteristic value.
- When the characteristic value reaches its maximal length or when the next connection event is due, a notification holding this characteristic value is queued for transmission, and the new readings are once again aggregated into the characteristic value.



Connection interval vs. current consumption for different BLE versions, for throughput = 4.8 kbps.

Discussion and Conclusions

- 300-Hz logging operation alone takes an average current of about 57 µA, while the BLE current depends on the choice of CI.
- The current decreases when larger CI values are chosen, because readings are aggregated into larger and fewer packets and the device wakes up less frequently to send them.
- When CI is sufficiently large (i.e. above ~300 ms), there is not much gain for further increasing CI.
  - This is because for a sufficiently large CI and throughput, approximately the same average number of BLE packets per second is required to achieve such throughput, and the power consumption is dominated by the radio transmission power rather than the consumption of other stages of the connection interval duration.
  - A delay of 400 ms is generally considered acceptable for EKG, however a lower CI can be chosen if needed. At CI = 400 ms, the current consumption is 133 µA, 93 µA and 77 µA on BLE 4.0, BLE 4.2 and BLE 5 respectively, which translates to a battery lifetime of 31, 45 and 54 days respectively on a 100 mAh small coin cell battery.

Thank You

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