An Assessment of Ultra Wide Band As an Alternative Controller for Bluetooth to Support High Rate Applications on Battery Powered Devices

Shady S. Khalifa, Hesham N. Elmahdy, Imane Aly Saroit and S.H. Ahmed

Abstract---Bluetooth is a low-cost, low-power wireless technology initially designed for cable replacement. With the new mobile lifestyle based on battery powered devices, Bluetooth came short in satisfying the needs of the high-rate applications due to its' limited data rate. Introducing BluetoothV3.0+HS specification in 2009, Bluetooth can now meet those demands by switching to an alternative controller based on IEEE802.11g radio. To this date there is no published work on the performance of IEEE802.11g as an alternative Bluetooth controller. Also, there has been no work related to the simulation of BluetoothV3.0 using the popular NS2 simulator. In this study, we present an implementation of BluetoothV3.0 in the NS2 simulator, discuss the shortcomings of IEEE802.11g as an alternative Bluetooth controller and propose a new alternative Bluetooth controller based on Time Hopping Impulse Radio Ultra Wide Band (TH IR-UWB) technology. The results showed that though IEEE802.11g provides high throughput than Bluetooth, it failed to do so in an energy efficient manner and is highly affected by interference. UWB succeeded to meet the goals of providing multiple high data-rate, low-power and immunity to interference, making UWB a better choice as a Bluetooth controller for high-rate applications running on battery powered devices.

Keywords---Bluetooth, Energy Efficiency, IEEE802.11g, NS2 Simulation, Ultra Wide Band

I. INTRODUCTION

APPLICATIONS with high-bandwidth demands such as high-quality video streaming have long found difficulties while using Bluetooth due to the low transmission rate allowing only disappointingly low-quality streaming. Attempts were made as in [1] allowing compressed high-quality video streaming over BluetoothV2.0 but still wasn't able to support high-definition video streaming.

BluetoothV3.0 specification [2] was released by the Bluetooth Special Interest Group (SIG) in 2009. The main addition to BluetoothV3.0 is the use of alternative controllers beside the Basic Rate / Enhanced Data Rate (BR/EDR) controller. An alternative controller consists of three layers:

- Protocol Adaptation layer (PAL) that maps the Bluetooth commands to the underlying layers and vice versa.
- Alternative MAC Protocol
- Alternative Physical Layer

For discovering the peer device alternative controller capabilities and managing connections over theses alternative controllers an Alternative MAC/PHY Manager Protocol (A2MP) was added in the BluetoothV3.0 specifications. Fig. 1 illustrates the BluetoothV3.0 protocol stack.

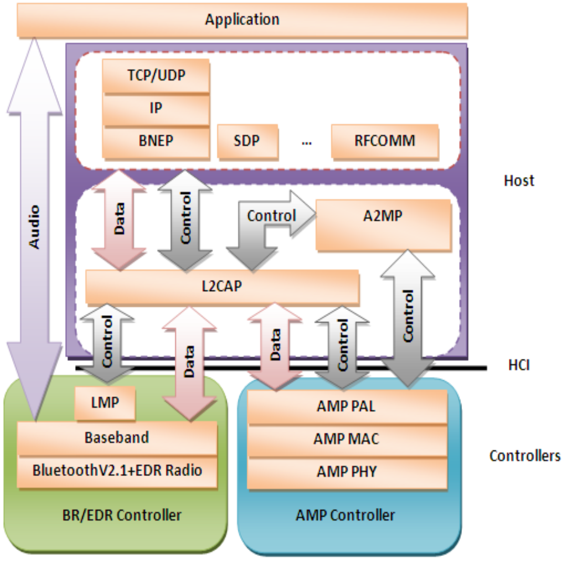

Fig. 1 BluetoothV3.0 protocol stack

The use of multiple-controllers (radio interfaces) allowed benefitting from the diversity between different radio-technologies. BluetoothV2.1 radio is used for connecting devices, service discovery and control message exchange, while the alternative controller offers high efficiency for large transfer of data. The idea of using two radio interfaces to benefit from the diversity between them is not new; the idea was studied before in [3, 4].

The utility of mobile nodes is directly impacted by their operating lifetime. Since they are battery-operated, energy becomes a critical resource where the wireless communication sub-system represents a major source of power consumption [5]. This is why the wireless communication subsystem power

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consumption must be carefully managed to ensure the longest running time before the battery is depleted.

Ultra Wide Band (UWB) technology entered the commercial market in 2002 when the FCC issued a Report and Order in which a definition for UWB transmission is proposed. UWB transmission is defined as any signal with a fractional bandwidth larger than 0.20 or which occupies a bandwidth greater than 500 MHz. To avoid interference with existing communication systems, the FCC has assigned the Effective Isotropic Radiated Power (EIRP) to -41.3 dBm/MHz in the unlicensed frequency band between 3.1 –10.6 GHz for UWB indoor communications [6], which is in fact at the unintentional radiation level of television sets or monitors.

UWB technology is promising in terms of providing high-rates, low-power and mitigation to interference. This meets the demands of high rate applications running on battery powered devices coping with the new mobile life style. In 2005 Bluetooth SIG announced that UWB is to be used as the alternative Bluetooth controller. The WiMedia Alliance; the body responsible standardizing UWB, then announced in March 2009 that it was disbanding causing Bluetooth SIG to use IEEE802.11 instead.

Studies were made in [7, 8, 9] to evaluate the performance of UWB as a Bluetooth controller. In [7], the authors studied the effect of the packet size and distance between nodes on the throughput using a single connection in their experiments. In [8], the performance of compressed high definition video transmission over a 1 meter link was evaluated. A comparison was made between Bluetooth over UWB and the Certified Wireless USB (CW-USB) in [9]. The authors studied the effect of the payload size on the throughput using a single connection in their experiments.

None of the previous studies evaluated the energy efficiency of using UWB as a Bluetooth controller, none considered the effect of collision and interference on the outcome in case of having more than a single connection at a time and none evaluated the performance at different traffic rates. In this study, we fill those gaps and provide a full picture of the performance of UWB as a Bluetooth controller for low and high traffic rates at different distances and different number of interfering nodes.

In this study, we present an implementation of BluetoothV3.0 in the NS2 simulator, discuss the shortcomings of IEEE802.11g as an alternative Bluetooth controller for battery powered devices and propose a new alternative Bluetooth controller based on Time Hopping Impulse Radio Ultra Wide Band (TH IR-UWB) technology. We then compare the performance of the proposed controller with that of BluetoothV3.0 specification over IEEE802.11g (BToWiFi) in terms of throughput and energy efficiency.

The remainder of this paper is organized as follows. In section II, we present our proposed alternative controller. In section III, we state the interference effect of Bluetooth, IEEE802.11g and UWB on each other. In section IV, the evaluation methodology is represented. In section V, a comparison is made between the two controllers and observations are interpreted. Finally, section VI concludes the paper.

II. PROPOSED CONTROLLER

In this section, the proposed controller components are presented. The proposed controller consists of TH IR-UWB physical layer, Dynamic Channel Coding (DCC) with interference mitigation MAC protocol and the UWB PAL.

TH IR-UWB is one of three different implementations of UWB. The other two implementations are Direct Sequence (DS) IR-UWB and Multiband Orthogonal Frequency Division Multiplexing (MB-OFDM). MB-OFDM approach has been primarily used for applications such as streaming video and wireless USB with data rates of 480 Mbps. Because of the high-performance electronics required to operate a MB-OFDM UWB radio, these systems generally don’t target the energy constrained applications. IR-UWB radios, however, can be designed with relatively low-complexity and low-power consumption. They therefore are very applicable to the energy constrained short-range wireless applications including WPANs, low-power sensor networks, and wireless body-area-networks [10]. A comparison between different UWB implementations in terms of Bit Error Rate (BER), throughput and energy efficiency for an indoor single-hop environment was conducted in [11]; the comparison results showed that TH IR-UWB provides better overall performance than MB-OFDM which in turn provides slightly better performance than DS IR-UWB. Using that information TH IR-UWB was selected for our proposed controller.

In this study we propose using TH IR-UWB with Pulse Position Modulation (PPM) in the lower band(3.1-4.85 GHz) of 1.75 GHz bandwidth, where time is divided into chips of short duration (T_c = 0.02 ns). The chips are organized into frames. The length of each frame is equal to the Pulse Repetition Period (PRP = 280 chips), large PRP value is used given Pulse Power (P_{pulse} = 100 pJ [12]) to minimize the radiated power (P_{rad}) defined as:

$$P_{\text{rad}} = \frac{P_{\text{pulse}}}{PRP \times T_C} \quad (1)$$

For medium access, one source will transmit one pulse per frame in a chip, the index of which is determined by the Time Hopping Sequence (THS) based on the communicating nodes MAC addresses. In addition, there is a predefined broadcast THS for all nodes.

Design requirements for an efficient IR-UWB MAC were studied in [13, 14]. A number of UWB MAC protocols were discussed and compared. It was concluded that the unique nature of UWB technology requires a MAC with additional features not observed in the existing MAC protocols of narrowband wireless communications. UWB requires a strict synchronization between transmitter and receiver, precision timing, long acquisition time and low power operation constraint for coexistence with other narrowband networks. Those requirements necessitate the development of a MAC optimized to UWB.

The DCC MAC proposed in [14] is a tailored MAC protocol for TH IR-UWB designed to maximize the benefit from the special UWB properties to achieve maximum flow control within the constraint of very low power emissions. DCC MAC allows competing sources to send simultaneously at the maximum power permitted by hardware and regulation constraints, sources then adapt to interference by dynamically adjusting their channel codes, thus their bit rates, causing rate reductions instead of collisions. By that DCC MAC allows interference to occur and adapt to it, in contrasts with the traditional interference management methods based on transmission power management and mutual exclusion. DCC MAC uses Rate Compatible Punctured Convolutional Codes (RCPC) providing variable encoding rate as well as incremental redundancy. Interference mitigation (IFM) scheme based on the concept of erasures is used in order to reduce the effect of an interfering close to the destination node. The DCC MAC protocol process is summaries as follows:

- Every node listens to its own THS.
- If a source (S1) wants to communicate with the destination (D1). It sends a transmission request on the destination's THS using the channel code for the lowest rate.
- D1 sends a reply using a THS private to S1 and D1 and the channel code obtained from the channel code assignment procedure.
- If S1 receives a reply, it indicates that D1 is idle and S1 starts transmission of the data packet using the THS private to S1 and D1.
- The source adds a Cyclic Redundancy Check (CRC) to the packet content and encodes it with the lowest rate code.
- The source then punctures the encoded data (i.e., removes specific bits from it) to obtain the desired code rate and sends the packet. The punctured bits are stored in case the decoding at the destination fails.
- Upon packet reception, the destination decodes the data and checks the CRC. If decoding is successful, an acknowledgement is sent back to the source. In addition, the packet contains a short header with the packet length, encoded at the lowest rate code. This ensures that the destination is able to detect that a packet transmission attempt did take place even when decoding of the entire packet fails. In such a case, the destination sends a negative acknowledgement (NACK).
- As long as the source receives NACKs, further packets with punctured bits (each time up to the size of the original packet) are sent, until transmission succeeds or no more punctured bits are available. In the latter case, the source retransmits the packet after a back-off period.
- After a transmission both source and destination nodes issue an idle signal on their THS respectively in order to inform other nodes that they are idle.
- If S2 tries to communicate with the destination D1 while S1 still sending data, it sends a transmission request on the destination's THS using the channel code for the lowest rate, but D1 is busy receiving from S1and will not send a reply, then S2 will have to wait to hear the idle signal from D1 and then waits for another random back-off time before retransmitting.

A new Protocol Adaptation Layer (PAL) was designed to handle the communication between the Bluetooth profiles and the proposed UWB MAC/PHY. The PAL function consists of the PAL management entity and the PAL Frame Convergence Sub-Layer (FCSL). The PAL management function contains command, event and link management. The PAL FCSL generates PAL packets by adding the PAL header and protocol ID to the original data and sends those packets to the UWB MAC. The PAL FCSL also removes the PAL header on receiving a packet from the UWB MAC before sending it up.

III. INTERFERENCE ANALYSIS

Coexistence between Wi-Fi and Bluetooth was studied in [15 16], As Wi-Fi uses a fixed frequency band of 22 MHz while Bluetooth hops between 79 bands each of 1 MHz, there is a probability of 22/79 that a Bluetooth packet hops in the Wi-Fi fixed frequency band leading to a collision. It was found in [15] that Wi-Fi packets suffer most from the 1-slot Bluetooth packets then 3 and 5 slots packets, so 5-slot packets are recommended when Bluetooth coexist with Wi-Fi as this would lead to a reduction in the Bluetooth hop rate, thus increasing the chances for a successful Wi-Fi packet reception. Though, if Bluetooth hops to the Wi-Fi channel during back-off period, there is no effect on Bluetooth packets. Regarding the Wi-Fi data rates, it was found in [15] that with a small number of Bluetooth nodes Wi-Fi high data rates can be used, but when Bluetooth piconets increase, Wi-Fi high data rate modes have to be abandoned. In [16], it was found that using Bluetooth voice traffic might be the worst of all interference cases causing a 65% packet loss for the Wi-Fi with a severe impact on the Bluetooth voice leading to a packet loss of 8%.

Coexistence between narrow band technologies and UWB was studied in [17]. The authors used high power IR-UWB transmitters that greatly exceed the FCC radiation regulations. It was found that both Wi-Fi and Bluetooth networks will slightly suffer only at high proximity from the UWB signals (less than 10 cm). Otherwise; there is no effect on their signals. Also it was found that Wi-Fi channels 1 and 5 are less affected by UWB signal than channels 9 and 13.

IV. EVALUATION METHODOLOGY

Using an alternative controller in BluetoothV3.0 adds a lot of potential to Bluetooth. To gain a deeper understanding about the issues of switching between the controllers, to compare candidate controllers and contribute to the research community in general, we have extended the UCBT [18] NS2 Bluetooth simulation model to model the BluetoothV3.0+HS core specification in a new model called the High Speed BlueTooth (HSBT) [19].

A. *Simulation Model*

HSBT was developed to provide an accurate modeling of the A2MP protocol and communication channels over the different controllers and to provide an interface to easy the operation of adding other controllers for future research.

HSBT model extends the UCBT model by adding the A2MP, 802.11 PAL and UWB PAL components. HSBT also modifies the UCBT by adding the capability of having more than one radio interfaces in a single Bluetooth node. The L2CAP component was also modified to establish logical links over the 802.11 MAC using the 802.11 PAL and over the UWB MAC using the UWB PAL. Finally, the 802.11 and UWB models were integrated, creating a simulation model for high speed bluetooth over IEEE802.11 or UWB.

For the alternative 802.11 MAC/PHY, NS2 802.11 model was used. For the alternative UWB MAC/PHY, EPFL [20] UWB extension for NS2 was used.

The HSBT model allows adding an IEEE 802.11b/g or UWB controller to the Bluetooth node, discovering the remote devices AMP capabilities and establishing links for data transfer over the alternative controller. Illustration of the HSBT simulation model components is represented in Fig. 2.

HSBT validation was performed using face validation through a cyclic model review and improvement process of logging the exchanged messages between communicating nodes during the AMP discovery, AMP link setting up and data exchange over the AMP link and compared with the Bluetooth specifications V3.0+HS.

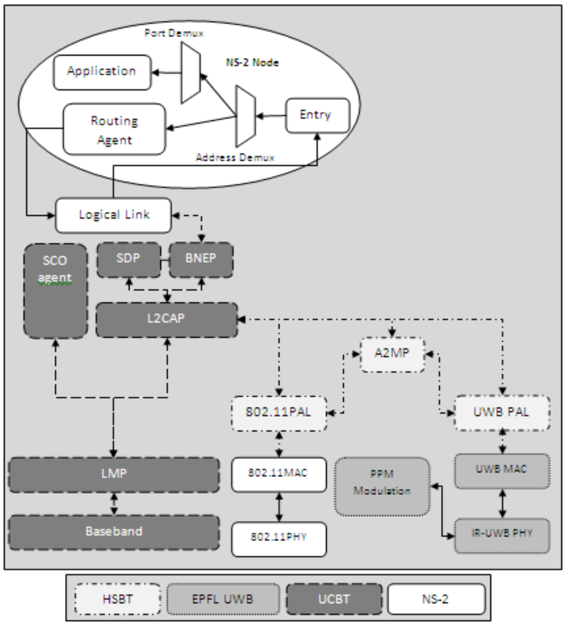

Fig. 2 HSBT BluetoothV3.0 node

B. *Simulation Environment*

A number of simulation scenarios were built to compare the performance of BluetoothV3.0 over IEEE 802.11g (BToWiFi) and BluetoothV3.0 over TH IR-UWB (BToUWB) in terms of throughput and energy efficiency versus number of connections and application data rate. In this analysis the BluetoothV2.1+EDR performance was used as a benchmark. Each scenario was run ten times. We calculated the 95% confidence intervals for the median for each set of the runs.The data obtained with the 10 replications for each of the two factor combinations was then examined using the analysis of two way variance routine to find the significance of each factor on the performance of the controller.

The simulation environment used in those scenarios represents the general operational indoor environment for Bluetooth. Simulation topology consists of a number of high-speed Bluetooth nodes with the same alternative controller in 8 meter by 8 meter area. Nodes are placed at random positions, and due to the limited range of Bluetooth (10 meters), the distance between any two nodes ranges from 0 to 8 meters. A connection is established between each 2 nodes, even nodes send while odd nodes receive. Nodes only send or receive to be able to do separate analysis on the transmitters and receivers. Connections between nodes are established within the first 2 seconds with a delay of 0.2 second between each connection establishment to prevent collision during connection establishment, while applications start transmitting data after 7 seconds and stops after 22 seconds from starting the simulation. All applications run a constant bit rate (CBR) traffic generator. Simulation ends only when there are no more packets to receive. By that we insure that the same amount of data has been generated and transferred in all scenarios with the same number of nodes and application data rate but different controllers.

In order to practically compare the power consumption, two wireless products for which detailed characteristics are publicly available are briefly presented as an example, including BlueCore 6 ROM Transceiver IC [21] from Cambridge Silicon Radio (CSR) and BGW211 Low-power WLAN 802.11g SiP [22] from NXP. For UWB, power consumption details are based on the 0.18mm CMOS presented in [12]. The current and power consumptions of the transmit (TX) and receive (RX) conditions for each interface are shown in Table I. The data shown are for particular products, although are broadly representative for examples of the same type. A detailed set of the simulation parameters used for different scenarios is represented in Table II.

TABLE I
CURRENT AND POWER CONSUMPTION FOR BLUETOOTHV2.1+EDR, IEEE 802.11G AND UWB INTERFACES

	Bluetooth [21]	802.11g [22]	IR-UWB [12]
VDD (volt)	1.8	3.3	1.8
TX(mA)	45	179	60
RX (mA)	45	114	54

TABLE II
SIMULATION PARAMETERS

Parameter	Values
BoWiFi Propagation Model	ITU Indoor Propagation Model • Distance power loss coefficient = 28 • Floor loss penetration factor = 0
BoUWB Propagation Model	Tarokh Propagation Model [23]
Initial energy (Wh)	3
Number of connections	1,2,3,4,5,6
Number of nodes	Twice the number of connections
Alternative controller	IEEE802.11g , DCC TH IR-UWB
Application	Constant Bit Rate (CBR)
Application data rate (Mbps)	1, 5, 10, 30
Application packet size (Bytes)	1400
Transport layer agent	UDP
Transport layer packet size (Bytes)	1500
Data size generated and transferred (Mbit)	15 × Application data rate

V. RESULTS AND ANALYSIS

A. Throughput

Average network throughput is one of the key quantitative metrics considered in the evaluation process. Average network throughput is calculated by averaging the connections throughput using (2).

$$\text{Throughput} = \frac{\sum_{i=0}^{Number\_of\_connections} \frac{R_i}{T(Last)_i - T(First)_i}}{Number\_of\_Connections} \qquad (2)$$

Where: R_i is the total number of bits received at the destination node of connection *i*.

- $T(Last)_i$ is the arrival time of the last data bit for connection *i*.
- $T(First)_i$ is the arrival time of the first data bit for connection *i*.

Two-way ANOVA for the network throughput is represented in Table III for both BToWiFi and BToUWB. As it can be seen for BToUWB there is no significance to the effect of the number of connections, only the application rate affects the network throughput. For BToWiFi both factors have nearby significance meaning that BToWiFi is highly affected by increasing the number of connections. Regarding the distance, both BToWiFi and BToUWB are not affected by the distance within an 8 m^2 area.

TABLE III
THROUGHPUT TWO WAY ANOVA FOR BTOWIFI AND BTOUWB

		df	SS	MS
BToWiFi	Number of connections	5	1486.7	297.3
	Application rate	2	991.7	495.9
	Connections*rate	10	1504.3	150.4
	Distance	162	0.16	1e-3
BToUWB	Number of connections	5	3e-12	7e-13
	Application rate	2	21604	10802
	Connections*rate	10	3e-12	3e-13
	Distance	162	3e-28	2e-30

The mean values of this metric are represented in Fig. 3, it shows that at a low application data rate (less than or equal the BluetoothV2.1+EDR maximum rate), the three technologies are equal in terms of network throughput. When the application data rate increases, BluetoothV3.0 benefit from the alternative controller high data rate to provide a faster data transmission.

The use of time division multiplexing and a different frequency hopping sequence per piconet allowed BluetoothV2.1+EDR to minimize the collisions and competence on the shared medium between connections, leading to maintaining the same network throughput with different number of connections. BToWiFi looses those benefits when it turns on the IEEE802.11g interface. To avoid collisions when IEEE802.11g interface is on, CSMA/CA is used which prevent a node from transmitting when the channel is not idle, making nodes wait for each other before transmitting. Thus, increasing the number of connections has a significant effect on BToWiFi. Not only that, throughput become even more affected by the number of connections as the application data rate increases, and the throughput drop caused by adding a single new connection increases.

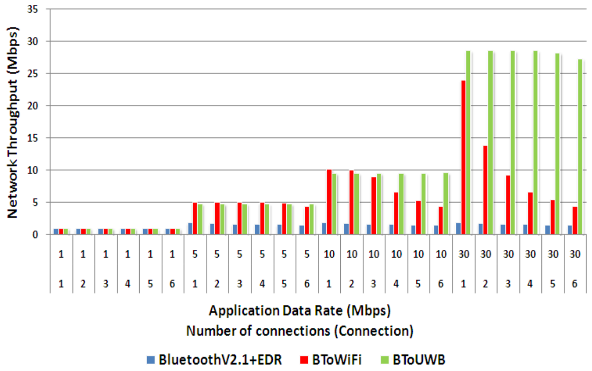

Fig. 3 Throughput of BluetoothV2.1+EDR, BToWiFi and BToUWB

With TH IR-UWB as the alternative controller, every connection has its own THS, so the throughput is not affected by the number of connection.

1) Energy Consumption per Bit

The other key quantitative metrics considered in the evaluation process is the average network energy consumption per bit. Average network energy consumption per bit is calculated by dividing the total amount of energy consumed to send and receive the data by the amount of data received. Average network energy consumption per bit is obtained using (3).

$$\text{Energy per bit} = \frac{\sum_{j=0}^{Number\_of\_Nodes} E_j}{\sum_{i=0}^{Number\_of\_connections} R_i} \qquad (3)$$

Where: E_j is the energy consumed at node j.

R_i is the total number of bits received at the destination node of connection i.

In the evaluation of the node energy consumption, the energy consumed by the Bluetooth and the alternative controllers in all of their states were considered.

2) *At low rates*

This metric shows as illustrated in Fig. 4 that at low application data rate, high speed BluetoothV3.0 benefits from the BluetoothV2.1+EDR low-rate, low-power radio interface to transfer the data, while IEEE802.11g and UWB can't benefit from their high transfer rates. As the energy consumption of IEEE802.11g and UWB is higher than that of Bluetooth and the high data rate is of no use at the low application data rates, BluetoothV3.0 becomes more energy efficient than both IEEE802.11g and UWB.

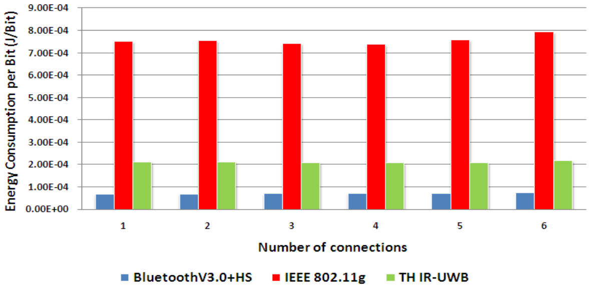

Fig. 4 Energy consumption per bit of BluetoothV3.0, IEEE802.11g and TH IR-UWB at 1Mbps

3) *At high rates*

At higher application data rates, BluetoothV3.0 switches on the alternative high-rate controller only to transfer data, then switch it off after the transfer completion, returning back to the Bluetooth low duty cycle to listen for new connection requests. This switching policy leads to lowering the total energy consumption, making BluetoothV3.0 more energy efficient than a standalone IEEE802.11g or UWB device. An IEEE 802.11g or UWB node in ad-hoc mode needs to be able to receive a packet from any node in the ad-hoc network at any time, which means that it needs to have its receiver active for long periods of time which consumes energy even if the node is not sending or receiving.

This metric as illustrated in Fig. 5 shows that BToWiFi becomes more energy efficient than BluetoothV2.1+EDR only at high application data rates (30 Mbps) and only for a small number of connections (up to 2 connections). Using IEEE802.11g as the alternative controller decreases the transfer time but it does so in an energy inefficient manner. BToUWB on the other hand is always more energy efficient than BluetoothV2.1+EDR. BToUWB energy efficiency even increases as the application data rate increase due to the decrease of the idle time and is not affected by the number of connections.

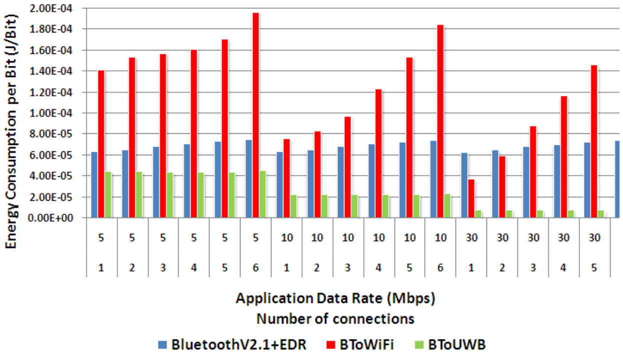

Fig. 5 Energy consumption per bit of BluetoothV2.1+EDR, BToWiFi and BToUWB for high data rates

VI. CONCLUSION

In this study we propose the use of DCC TH IR-UWB as an alternative controller for BluetoothV3.0 instead of IEEEE802.11g. The two alternative controllers are then evaluated by means of computer simulations in terms of throughput and energy efficiency. The impact of the distance between end nodes and that of the interference caused by neighboring nodes was considered.

The simulation experiments herein reveal that BluetoothV3.0 has made benefit of the BluetoothV2.1+EDR radio low power to overcome the high power consumption of IEEE802.11g and UWB at low application data rates and idle state.

Also BluetoothV3.0 has made benefit of the high data rate of IEEE 802.11g or UWB for a faster transmission making BluetoothV3.0 more energy efficient than a standalone IEEE802.11g or UWB.

We also conclude, based on the results of simulations that IEEE802.11g has increased the throughput but in an energy inefficient manner and its throughput is highly affected by the number of connections and application data rate, making it a bad choice for battery powered devices. DCC TH IR-UWB on the other hand, provides better overall performance in terms of throughput, energy efficiency and ability to work in a more crowded environment providing a better choice as a Bluetooth low-power, high-rate alternative controller.

The DCC MAC still can't support transmitting uncompressed video streams due to its limited rate. The limited rate is caused by the large PRP used in order to minimize the energy consumption. The UWB field is still young; a lot of research is still required to reach an optimal MAC that can provide low-power and high-rates.

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