

# A Body-Coupled Communication and Radio Frequency Dual Technology Cooperation Protocol for Body-Area Networks

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**Abstract**—Body-area networks (BANs) are wireless sensor networks (WSNs) that operate in close proximity to the human body, being used for example for distributed wireless medical body sensors. Current implementations of BANs use standardized radio frequency (RF) technologies like IEEE 802.15.4, and do not account the characteristics of the body channel, e.g. strong attenuation of high frequency radio waves. In order to provide high reliability as well as energy efficiency while communicating close to the human body, a new technology called body-coupled communication (BCC) was developed. As it uses the human body as channel, it does not suffer from shadowing and enables efficient and reliable data communication between nodes in close contact with the human body. As many applications still require to transmit some data few meters from the human body, it is essential to also have RF capabilities in a BCC-BSN. In this paper we propose a new BAN node architecture where all nodes have both a BCC and RF transceiver. We propose a protocol that enables the cooperation between the two technologies. We present the hardware and software system implementation and illustrate our concept with measurement results. We show that our dual technology solution is more efficient and reliable than classical RF solutions for BANs.

## I. INTRODUCTION

In many application domains where sensor networks are deployed around the human body, communication reliability is usually crucial (e.g. healthcare). These sensor networks are primarily implemented using classical radio frequency (RF) technology, e.g. IEEE 802.15.4, and operate in the industrial, scientific and medical (ISM) radio band. However, RF signals suffer considerably from body shadowing [1], [2] in a highly variable way with respect to human movement [3]. This makes communication between on-body nodes, and also off-body nodes, very unreliable. Furthermore in certain medical scenarios, multiple sensor nodes are deployed in several different places on the human body. For example consider a person that has a node on the torso and one on the back. It is possible that the node on the torso can communicate perfectly with an off-body gateway node located in front of the body, but the node that is positioned behind the person cannot.

For addressing the aforementioned problems in BANs, a number of works have been developed and we review the most noteworthy mechanisms next. A two-level communication

protocol named TLC was presented by [4]. In that work the authors proposed the use of two different RF bands namely the 433MHz and 2.4GHz. The 433Mhz band is used for data aggregation whereas 2.4Ghz band is used to send the aggregated data to a base station. Since the range of the 433Mhz band is limited to approximately 2 meters around the node it is possible to improve the reliability and energy consumption by reducing the number of nodes competing for the same channel and reducing the number of collisions. Other notable work done in this area includes LEACH [5]. This is a clustering-based routing protocol that minimizes global energy usage by distributing the load to all the nodes at different points in time. Finally, in [6] the concept of using a fuzzy logic controller over the MAC layer protocol is introduced.

But all the aforementioned works are still based on RF technology which suffers from fundamental limitations. We believe that there is a need for a new communication paradigm that improves substantially the reliability of highly critical medical applications. In line with this thinking, we have identified one technology that has the potential to solve in part the aforementioned problems, that is body-coupled communication (BCC) [7],[8]. BCC is a communication technology that uses the human body as the communication channel. BCC transmitters generate low power electric fields on the surface of the human body, and the variations of the field are sensed from any attached receiver. Hence, this is a communication mechanism that does not use EM radiation. One of its advantages is that for nearly every location on the human body the propagation loss is well below 80 dB[9]. The work in [9] also demonstrated that body movement results in only small variations in channel attenuation. Another positive aspect of the BCC technology is that hardware transceivers have been shown to be very efficient. The work in [10] presented a solution which has an energy efficiency of 0.37 nJ/b at 10 Mb/s, i.e. three orders of magnitude more efficient than IEEE 802.15.4. Also at the medium access control (MAC) layer it was shown that it is possible to reduce even further the energy consumption by suppressing contention waiting time and by using an energy-wise optimal packet structure [11]. Therefore, BCC looks a very promising technology for exchanging information be-

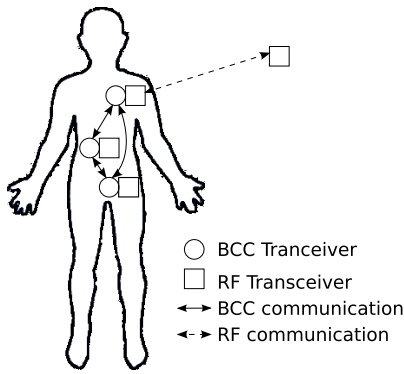


Fig. 1. Example of BAN with BCC/RF nodes on the body.

tween several nodes placed on the human body. Nevertheless, in most applications it is required to transmit data outside the human, e.g. to a gateway, in order for the information to be processed with higher computing capabilities than what is generally available on a sensor node. Therefore it is still desirable to have RF capabilities in a BAN.

In this paper we propose a novel BAN architecture where all nodes on the human body are equipped with both RF and BCC transceivers and is depicted in Figure 1. Nodes use BCC for on-body communication, while an RF link is used for reaching nodes off the body. For RF communication IEEE 802.15.4 was used. The BCC technology is the one presented at [10], [11]. Our contribution is a new communication protocol that makes use of both technologies by operating on top of the MAC layer and it ensures that they cooperate efficiently. This protocol is named the dual technology cooperative (DTC) layer and its architecture is illustrated in Figure 2. The application layer communicates directly to the DTC layer which makes the use of different PHY layers transparent to the application.

## II. SYSTEM OVERVIEW AND PRELIMINARIES

In this section we present the DTC protocol that enables BAN nodes on the human body to utilize both their BCC and RF transceivers efficiently. The main motivation for using two technologies is that the RF transceiver with the best link quality is not necessarily attached to the node that needs to transmit a message to an off-body node. Therefore, in this case it is preferable to forward the message with BCC to the node that has the best RF link. However, depending on where an off-body node is positioned, the on-body node with the best line of sight (LOS) to this off-body node will change over time. This means that the relay node should be selected dynamically. It is also possible that an off-body node might want to transmit information to an on-body node. In that case the DTC layer must insure that the information will be received with a maximum guaranteed delay. This is accomplished by keeping a subset of the RF transceivers in active mode in order to receive incoming packets. *In summary the goal of the proposed DTC layer is to automatically select the optimal node on the body to transmit or receive from an off-body node, independently on where the information is generated.*

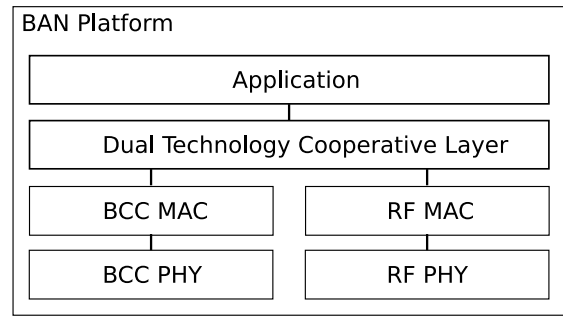


Fig. 2. BCC/RF platform architecture.

### A. Protocol Overview

The DTC/network layer is subdivided into two interdependent modules, a *protocol automata* and a *fuzzy controller*. The protocol automata defines the behavior of the DTC layer based on specific parameters that we explain later. Three characteristic behaviors for the DTC layer were identified and are described in detail below. During run-time the algorithm changes dynamically in the space limited by these three behaviors. The fuzzy controller sets the parameters of the algorithm depending on input from application layer (e.g. required throughput, sensor measurements) and feedback from the protocol automata module. In summary the fuzzy controller selects the composition of behaviors that should be used.

### B. Behaviors of the DTC layer

Three dimensions have been identified in the design space. They are illustrated in Fig. 3, while we analyze them in detail next.

1) *Measurement-based*: In the case of a measurement-based behavior, the DTC layer selects a relay based only on measurements, e.g. the RF link quality indicator (LQI) to the off-body node. Obviously nodes with higher LQI have higher probability of success while transmitting to an off-body node. It is also possible to achieve energy savings with the use of power control. However, maintaining up-to-date measurements from all on-body nodes to all off-nodes is expensive in sensor networks. It requires sending special packets if the traffic is low, keeping track of large tables of data, and communicating on-body to share the measurements. There is clearly a trade-off between the savings due to reliable communication and the loss due to overhead to maintain measurement tables. It is also worth to note that if the measurements vary quickly the associated overhead for updates is large. However, for an environment that is fairly constant then the overhead cost is negligible.

2) *Random-based*: In the case of a random behavior, the DTC layer selects a relay at random. It has been observed that in sensor network clusters, an element of randomness in the selection of a cluster head increases the overall life of the network by avoiding quick draining of some unlucky nodes [5]. The optimal amount of randomness in the relay selection may vary with different surrounding conditions and motion of the human body. That is why an attempt is made

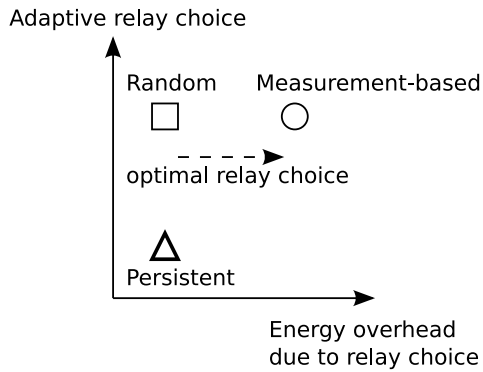


Fig. 3. Different behaviors of DTC layer.

to quantify randomness and include it in our model. Note that the random behavior has the inverse property compared to the measurement-based behavior. In case of frequent changes in the network, the random behavior has no additional overhead. However in case of a stable network it is always suboptimal.

3) *Persistent-based*: In the case of a persistent behavior, the DTC layer of a node does not select a relay, but instead it persists on using its own RF transceiver. Persistence through re-transmissions or Automatic Repeat-reQuest (ARQ) is a fundamental mechanism for error control in communication networks. A pure persistent behavior is what typical RF networks would have performed in this case. The key here for the DTC layer is to decide how many times it should retry and then to which other behavior it should switch depending on the results.

### C. Design Space Parameters

The operating point of the algorithm will be located at a point in the design space that is limited by the aforementioned behaviors. The most important parameters that determine this operating point of the algorithm in the overall design space are presented next.

- $N$ : Number of nodes in the network.
- $n$ : Number of times a non-relay node attempts to transmit a message before forwarding it. This parameter controls the persistence of the node that generated the data packet. A high value for this parameter results in operating the BAN similarly to a typical RF-based network.
- $m$ : Number of times a relay node attempts to transmit a message before forwarding it. This parameter controls the persistence of the remaining nodes of the network. At least one relay is chosen and attempts to transmit the packet.
- $r_R$ : Ratio of nodes in the network that are relay nodes. This parameter controls the size of the set of relays, therefore directly controls the randomness.
- $E_{min}$ : minimum energy level required for a node to be taken into the set of relays. This directly controls the measurement dependence, the higher this level is set the more frequently nodes are removed from the set of relays.

- $T_R$ : refresh period for LQI values of relay nodes. If a node who is in the set of relays has been idle for some time its LQI would need to be updated, this parameter sets the value for the maximum period after which an update in LQI is required.

## III. PROTOCOL OPERATION

The operation of the DTC layer is separated in three parts, namely the creation and maintenance of relay sets, the transmission to an off-body node, and the reception from an off-body node.

### A. Creation of Relay Sets

One of the most important tasks of the protocol is to establish a set of nodes that can act as relays for offloading data to off-body nodes. A node is qualified to become a relay by having an LQI above a certain threshold. If no node is above this threshold then the node with the best LQI is chosen. Note that as we increase this threshold, the algorithm approaches a measurement-based behavior. In this ways the set of available relays  $R$  for off-body node  $D$  is established, i.e. this set is  $R(D)$ . A set of relay nodes is established for every off-body node that the BAN needs to communicate with, i.e., one separate set for every off-body node. Every node in the body has the same set of relays. Now, whenever a node has to use a relay, it randomly selects one node from the set of relays and forwards the message to it. The randomness of our algorithm is controlled by the size of these sets, whereas among the nodes inside the sets every node has an equal probability to be selected to act as the active relay for a particular message, regardless of the RF link quality (i.e., uniform distribution). A pure measurement-based behavior has a set of size one.

### B. Maintenance of Relay Sets with Token Passing

However, due to the dynamic behavior of RF link quality this relay set  $R$  changes constantly. The mechanism we designed for updating this set is described next. The election of relay nodes is done based on a token bus mechanism in which incremental addresses form a ring. The number of tokens is equal to the size of the set  $R$  in stable state. Tokens circulate the network until they find a suitable node that has LQI higher than the defined threshold. Only nodes in possession of the token try to obtain new LQI values in order to check whether they are eligible as a relay. Note that the best nodes are not necessarily selected as relays. It is possible that the set of relays is populated with nodes that have small LQI but it is still above the threshold. A token passing mechanism is selected to serialize the creation of sets so that this process does not create contention in the RF network and a high number of collisions. Finally, each relay node has to refresh the RF LQI periodically. The LQI update request has to be initiated by the gateway node. The LQI is also refreshed automatically when receiving any packet from the off-body gateway.

Every node creates tokens until their number is equal to  $r_R N$ . The created tokens have a sequence number, a next holder address, and the address of the off-body node for

which the token is created. Token creation and token passing is done through broadcast packets in the BCC network and only the node which is the next holder replies with an acknowledgement packet. All nodes keep a table of all the tokens present in the network. This table is updated whenever token creation or token passing happens. If a node misses both a token activity packet and the following acknowledgement packet, it will have an outdated token table. This could mean that the node tries to select a node as a relay that does not have a token any more. If this happens then the node which is being mistakenly selected as a relay will reply back with an update on the last known location of the token.

When a node receives a token packet it generates a request for LQI from the off-body node to whose set the token belongs to. Upon receiving the LQI request response, the LQI is compared to  $E_{min}$ , and if the LQI is over the threshold the token is kept, else the token is forwarded. If a node is already in the set of relay nodes and receives a token it simply forwards it on to the next one without performing any test. If extra tokens are created they are destroyed upon their discovery. Tokens may also be destroyed on disassociations and by changing the parameter  $r_R$ .

### C. Packet Transmission and Reception

1) *Transmission to off-body nodes:* When a non-relay node wants to send data to an off-body node, it sends it a maximum number of  $n$  times by itself. If it still fails to get an acknowledgement it selects a random node from the set of relay nodes and forwards the packet to it. When a node in the set of relays has to send data to an off-body device; whether it is the source of the data or acting as a relay the procedure is the same. The node will try to send the packet  $m$  times. If it is not able to get an acknowledgement it will select another random relay and forward the data to it, it will also remove itself from the set of relay nodes by passing the token to some other node. In case it is able to get an acknowledgement from the off-body device it will update its LQI from the acknowledgement. If the LQI is more than  $E_{min}$  it resets the LQI timer, but if the LQI is less than  $E_{min}$  it removes itself from the set of relays by passing the token.

2) *Reception from off-body nodes:* A similar scheme is used for receiving data from off-body devices. In the set of relay nodes, one node is always awake. It sends a packet using BCC to another node in the set when it goes to sleep to make it the reception relay. When a packet arrives it is received by the reception relay and forwarded to the true destination with BCC.

## IV. ENVIRONMENTAL AND MEASURABLE PARAMETERS

Due to the design and computational complexity of conventional adaptive control systems, a decision was made to use a fuzzy control system based on a matrix of rules. After this step there is a need to find methods to measure and quantify these factors in order to realize the control system. Then the matrix of rules that make up our control system is filled. There

are many factors expected to affect the position of the optimal point in the behavior space.

- *Surrounding environment* (type and size of room, obstacles and interfering devices): if all nodes can get good signals from the off-body node then a persistent approach is the best.
- *Network traffic:* High network traffic may justify a high control overhead to get in return high reliability.
- *Distance from the off body device:* if the distance from the body to the off-body device is short, then all nodes will have high LQI which tends to disqualify a measurement-based approach.
- *Motion of the body:* LQIs and thus the probability of a node to reach an off-body node might be rapidly changing, a measurement-based approach will have high overhead, randomness is more appropriate.
- *Posture of the body:* posture of the body might also affect the LQI at a particular node.
- *Number and position of nodes on the body:* if all nodes are placed very close to each other there might be no point in maintaining a large set of relays.

Although these parameters are expected to directly affect the position of the optimal point in the behavioral model of the DTC layer, it is difficult to estimate their value at the sensor nodes themselves. Therefore, metrics that are easily measurable in practice have to be used. The measurable parameters that could be used are:

- Average LQI
- Standard deviation of LQI for a certain node
- Standard deviation of LQI over space (between different nodes)
- Data traffic
- Number of nodes
- Average packet hop count

The average value of the LQIs of all the nodes can serve as an indication of the distance to the off-body node. Similarly the standard deviation of the LQIs over space between the nodes can be an indication of the posture of the body and the relative positions of the nodes on the body. The standard deviation of the LQIs over time can be used to indicate the motion of the body. A high average packet hop count can act as a feedback to measure the efficiency of the network layer.

## V. IMPLEMENTATION

In order to study the concept of a dual technology solution and show that it can provide better reliability than a simple RF based system for BANs, we implemented the DTC layer and we performed real-life experiments. The system that we used was composed on two modules, namely an experimental BCC board (Figure 4) and a CC2430-based board (Figure 5) connected through UART (universal asynchronous receiver/transmitter).

The experimental BCC board is a hardware module designed to demonstrate the BCC principles as well as typical applications that can be realized with this technology. It is

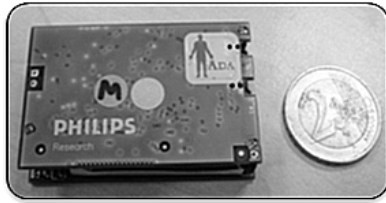


Fig. 4. Experimental BCC board

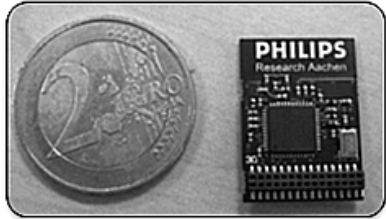


Fig. 5. CC2430-based board

TABLE I  
EXPERIMENTAL RESULTS

$n$	$n$	$m$	Packet success rate
2	6	0	0.56
2	0	6	0.95
2	3	3	0.99

based on an MSP430 microcontroller, an AVR microcontroller and a BCC transceiver. The AVR was used for digital signal processing and physical layer of BCC. The MAC layer, the DTC layer, and the application are executed on the MSP430. For the RF module the CC2430 chip that is equipped with an IEEE 802.15.4 transceiver was used.

## VI. EXPERIMENTAL RESULTS

In our initial experiments we used three nodes, two of them were dual technology nodes, equipped with both a BCC and a RF transceiver and are placed on the body. The last node was a IEEE 802.15.4 coordinator placed outside of the body. The on-body sensor nodes periodically send data to the off-body node. During the experiment we measured the rate of successful packet transmissions, which is the number of received packets over a specific time duration. The parameter  $r_R$  is set to 0.5. A dynamically changing environment was emulated by covering the RF antenna of the both CC2430 turn by turn using hands, so that one on-body node cannot send or receive any packets from the off-body node. For this experiment the on-body nodes were placed close together to ensure that there were no packets lost in the body coupled communication.

Table I gives the results for the experiment. In the settings  $(n, m) = (6, 0)$ , the network behaves like a simple RF network in which a node tries to send data six times if it is unable to receive an acknowledgement. In these settings 56% of the packets were received. Although one of the nodes was kept blocked at all times, the percentage of packets received is slightly more than fifty percent, simply because human hands do not provide perfect blocking. The next two measurements

show that a DTC network can provide a much better reliability over a simple RF network in certain operating conditions.

## VII. CONCLUSION

In this paper we presented a new body area network architecture where all the sensor nodes are equipped with both RF and BCC transceivers. Since BCC is energy-efficient and reliable it is always used for on-body communication. For efficient off-body communication we developed a DTC layer that selects the most appropriate RF relay node on the body to communicate with the wireless access point. We presented the theory behind the proposed protocol and also the developed platform. The first implementation results indicate the efficacy of the proposed scheme in real-life conditions. As future work, we plan to conduct more extensive tests under different conditions of the wireless and body channels. Furthermore, we plan to extend the proposed protocol so that it can optimize in a synergistic fashion several system parameters like the energy, throughput, and latency.

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