Experimentally-based Cross-layer Optimization Across Multiple Wireless Body Area Networks

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Abstract—In this paper, we investigate cross-layer optimization performance based on real-life experimental measurements, at the physical and network layers, across coexisting wireless body area networks (BANs). At the network layer, the best possible route is selected according to channel state information from the physical layer. Two types of dynamic routing are applied—shortest path routing (SPR), and novel cooperative multi-path routing (CMR) incorporating 3-branch selection combining. These routing techniques are used for performing real-time, reliable data transfer across BANs operating near the 2.4 GHz ISM band. An open-access experimental dataset incorporating ‘everyday’ mixed-activities is used for implementing and analyzing the proposed cross-layer optimization. In terms of outage probability, negligible packet error rate is achieved by applying CMR and SPR techniques with reasonably sensitive receivers. Moreover, up to 8 dB performance improvement is gained by applying CMR over SPR, at 10% outage probability. The amount of end-to-end delay obtained from SPR and CMR schemes are 76 ms and 129 ms, respectively. Also, the combined channel gains across SPR and CMR are lognormal and Weibull distributed, correspondingly. The acquired empirical results comply with the IEEE 802.15.6 Standard for packet error rate and latency for both medical and non-medical BAN applications.

Index Terms—Cross-layer optimization, dynamic routing, IEEE 802.15.6, wireless body area networks.

1 INTRODUCTION

Wireless body area networks (BANs) are often specifically designed for health-care scenarios to autonomously connect various medical sensors and actuators located on, around or near the human body to monitor physiological signals. Although, BAN applications span a wide area from military, ubiquitous health care, sports, entertainment to many more [1], advanced professional health care management is one of the main purposes of the BAN concept. However, the underlying technology is still at an early stage of deployment and typically based on very specific wireless communications technologies [2]. The IEEE 802.15.6 BAN Standard aims to enable low-power communication to be reliable and practical for in-body/on-body nodes to serve a variety of medical and non-medical applications. Now patients with BANs can be monitored while carrying out their regular everyday activities, without being tethered to monitoring devices.

With the anticipated growth in the number of people using BANs, their co-existence will be a concern in the near future. When multiple closely-located BANs coexist, the potential inter-network communication and cooperation across BANs lead to the investigation and design of wireless body-to-body networks (BBNs) [3], [4]. The main motivation behind BBN is to overcome and make use of the problems of co-existence, which include: inter-BAN radio interference dominating on-body transmissions, increased power consumption, larger end-to-end delays and general performance degradation for closely located BANs. Due to the high mobility nature of BANs, it is generally not feasible to assign a central coordinator among BANs to maintain coexistence [5]. Hence, to improve network connectivity and robustness, practical optimization frameworks should be developed. In this paper, we perform cross-layer optimization across the physical and network layers for two-tiered communications, on-body BAN at the lower tier and BBN at the upper tier. The analysis is applied to an open-access radio measurement dataset provided in [6] recorded from ‘everyday’ mixed-activity and a range of measurement scenarios with people wearing radios. The extensive radio channel data was captured using NICTA developed wearable channel sounders/radios. Our key findings in this paper, based on empirical data from real-life measurements, are as follows:

- Negligible (almost 0%) packet error rate (less than 10%, thus fulfilling the requirement of the IEEE 802.15.6 Standard) is achieved with reasonably sensitive receivers for both shortest path routing (SPR) and cooperative multi-path routing (CMR) in a dynamic environment associated with mobile subjects, using the available nodes/hubs as relays.
- The proposed CMR provides up to 8 dB performance improvement over SPR, at 10% outage probability.
- SPR provides better performance relative to average end-to-end delay than CMR technique, while both satisfying the IEEE 802.15.6 latency requirement.
- The empirical received signal amplitude through SPR has a lognormal distribution while the empirical received signal amplitude through CMR has a

References:

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The rest of this paper is organized as follows: In Section 2, related work to cross-layer optimization for wireless body area networks is described. The system model with the experimental scenario is presented in Section 3. Section 4 elaborates the two routing techniques incorporated with physical layer processing, mentioned in the system model section. The experimental results of outage probability and average end-to-end delay for measuring the performance of the network are analyzed and compared with theoretical analysis in Section 5. Additionally, the probability distribution functions, fitted to combined channel gains after routing is applied, are provided. Section 6 provides some concluding remarks.

2 RELATED WORK

Many studies have been focused on BANs for medical purposes [7], [9], [10], [11], [12], [13]. However, few works have been concerned with a global solution for tens or hundreds of patients, each of whom is fitted with multiple sensor nodes, and confined to a relatively small environment [2]. Cross-layer approaches between non-adjacent layers (e.g. PHY-Network layer) with creation of new interfaces or vertical calibration (sharing runtime information between layers) is an important option to consider for BANs, especially when there are many of them closely located. In the past decade, several cluster-based and cross-layer routing protocols have been proposed for BANs along with other routing protocols [14]. Some of the cluster-based routing protocols (e.g. ANYBODY [15], HIT [16]) that have been designed for BANs aim to minimize the number of direct transmissions from sensors to the base station. WASP [17], CICADA [18], TICOSS [19] and BIOCOMM [20] are some cross-layer protocols between Network and MAC layer for BANs. Amongst these protocols, TICOSS and CICADA consume less energy, whereas the WASP scheme outperforms others in terms of efficient packet delivery ratio (PDR) [21]. Also, CICADA performs well among the other protocols in terms of reducing packet delivery delay [21]. Ota et al. proposed an energy-saving MAC protocol, DQBAN (Distributed Queuing Body Area Network) for BAN in [22], as an alternative to the 802.15.4 MAC protocol which suffers from low scalability, low reliability and limited QoS in real-time environments. The proposed DQBAN is a combination of a cross-layer fuzzy-logic scheduler and energy-aware radio-activation policies [23]. The fuzzy-logic scheduling algorithm is shown to optimize QoS and energy-consumption by considering cross-layer parameters such as residual battery lifetime, physical layer quality and system wait time [23]. A Cross-layer Opportunistic MAC/Routing protocol (COMR) [24] has also been proposed for improving reliability in BAN, where the authors have used a timer-based approach with combined metrics of residual energy and RSSI as their relay selection mechanism in a single BAN and compared it with Simple Opportunistic Routing (SOR) [25]. In [26], the authors have proposed an efficient cross-layer reliable retransmission scheme (CL-RRS) without additional control overheads between physical (PHY) and MAC layer, which significantly improves frame loss rate and average transmission time as well as reduces power consumption.

The proposed routing protocols thus far, either do not consider postural body movements with mobility or are not as energy efficient as possible. Additionally, most previous routing protocols for BANs have not considered reliability and Quality of Service (QoS) [14]. Whereas, the cross-layer methods described in this paper can incorporate postural body movement and mobility together with routing, with excellent communication reliability across BANs.

3 SYSTEM MODEL

We assume a two-tiered network architecture formed from 10 co-located mobile BANs (people with fitted wearable radios) deployed for experimental measurements, where the hubs of the BANs are in tier-2 in a mesh (inter-BAN/BBN communication) and the on-body sensors of the corresponding BANs are in tier-1 (intra-BAN communication). An abstraction of the architecture is given in Fig. 1 with four co-located BANs. It can be portrayed as a hybrid mesh architecture where BANs (hubs/gateways) are performing as both clients and routers/relays, which will enable flexible and fast deployment of BANs to provide greater radio coverage, scalability and mobility. A given node, when acting as relay, follows the decode-and-forward relaying scheme for which it decodes the signal and then retransmits it. Dynamic routing is performed in a cross-layered approach, with two different routing techniques, i.e., shortest path routing (SPR) and cooperative multi-path routing (CMR), that utilize and interact with the physical layer. Therefore, changes in channel states are directly indicated from the physical layer to the network layer, so that the routes with most favorable channel conditions are chosen. The routing techniques are further described in the following section.

3.1 Experimental Scenario

The open-access dataset on which we base our analysis, consists of extensive intra-BAN (on-body) and inter-BAN (body-to-body) channel gain data, captured from 10 closely
transmits in a round-robin fashion, at 2 ms separation between each other. Hence, each transmitter is transmitting in every 50 ms to every 9 other subject’s receivers as well as their own receivers (all small body-worn radios/hubs/sensors), along with capturing the RSSI (Receive Signal Strength Indicator) values in dBm. For any given link, the samples are taken periodically over continuous time slots of 300 ms for real-time dynamic estimation, given the coherence time for both on-body and off-body ‘everyday’ channels is around 500 ms [28]. Due to the reciprocity property, the channel from any Tx (transmitter) at position a to Rx (receiver) at position b, is similar for Tx at b to Rx at a [27], thus transmitters and receivers can be considered interchangeably.

4 PROPOSED ROUTING APPROACH

The notion of BBN is more dynamic and potentially large-scale, where each BAN member can join and/or leave the network seamlessly, without the need for any centralized infrastructure. Hence, dynamic routing is necessary to enable routers to select paths according to real-time logical network layout changes by periodic or on-demand exchange of routing information. In routing, by applying ad-hoc mode at the physical layer and mesh routing at the network layer, pure client-to-client wireless mesh networks can be designed without any need for a centralized coordinator or an access point. Here, we have implemented dynamic routing based on Open Shortest Path First (OSPF) protocol, which uses Dijkstra’s algorithm.

4.1 Dynamic Shortest Path Routing (SPR)

We perform dynamic shortest path routing (SPR) [29] with experimental measurements based on link-state algorithm, where the source nodes intend to find routes with a minimum cost (based on routing metrics) to their destinations and update the routing table dynamically to adapt variable channel conditions and topological changes. Routing metric predicts the cost of the route calculated from the use of a certain routing protocol, which plays a critical role in finding out the efficient route to the destination in a network. For investigating the performance of dynamic routing, we use a combination of different routing metrics (e.g. ETX, hop count etc.).

Hop count: Hop count identifies the route which has minimal number of hops. The primary advantage of this metric is its simplicity. Once the network topology is known, it is easy to compute and minimize the hop count between a source and its destination. However, the primary disadvantage of this metric is that it doesn’t take packet loss, bandwidth, power consumption or any other characteristic of a link into account [30].

ETX: The Expected Transmission Count (ETX) path metric is a simple, proven routing path metric that favors high capacity and reliable links. This metric estimates the number of retransmissions required to send unicast packets by measuring the loss rate of broadcasted packets between pairs of neighboring nodes [30], which can be calculated as follows:

$$ETX = \frac{1}{1 - O_p},$$  (1)

where $O_p$ is the outage probability.

ETX adds more reasonable behavior under real life conditions, since this metric is based on packet loss and thus the number of packets sent.

In this paper, an optimal path is selected by combining these two metrics (ETX + Hop count), restricting the hop count to two hops. A pseudocode for this process is given in Algorithm 1. In Fig. 3, an illustration of shortest path routing (SPR) is presented, where the difference between the ETX metric and combination of metrics (ETX + maximum 2 hops) is demonstrated. The path taken using the ETX metric can be a longer path with the lowest cost. However, the path associated with combined metric (ETX + max. 2 hops) is an optimal path, having the lowest cost possible with a maximum of 2 hops.

4.2 Dynamic Cooperative Multi-path Routing (CMR)

Multi-path routing yields better performance than single-path routing by providing simultaneous parallel transmissions with load balancing over available resources. The change from single-path routing to multi-path routing needs a significant modification in the routing protocol rather than just parameter adaptation [31]. Hence, cooperative multi-path routing (CMR) has been considered in [32]. We propose a new CMR scheme that employs 3-branch selection combining within individual route paths, incorporating shortest path routing (SPR) and improving the performance of SPR.

Here, in dynamic cooperative multi-path routing, we use multiple alternative paths from source to destination with
cooperatively combined channels in each route-hop. In this paper, route-hop refers to each hop of a route in CMR from source hub to destination hub through an intermediate BAN hub (acting as a mesh router/relay). In each route-hop, 3-branch cooperative selection combining is used, where one of the branches is the direct link and the other two branches have two link-hops. Link-hop refers to each hop from a BAN hub through on-body relays of the corresponding BAN. A decode-and-forward protocol is applied at each on-body relay. The equivalent channel gain at the output of selection combining can be estimated as follows:

$$h_{sc}(\tau) = \max \left\{ h_{sd}(\tau), h_{sr,1}(\tau), h_{sr,2}(\tau) \right\},$$  \hspace{1cm} (2)$$

where $h_{sc}(\tau)$ is the equivalent channel gain at the output of the selection combining, at time instant $\tau$. $h_{sd}$ is the channel gain from source-to-destination (direct link), $h_{sr,1,d} = \min\{h_{sr,1}, h_{sr,2}\}$ are the channel gains of the first and second cooperative relaying links (with two link-hops, $s$ to $r_i$, and $r_i$ to $d_i$, $i = [1,2]$, respectively.

For multi-path routing here, 2 paths are used from source hub to destination hub, where both paths have two route-hops. The shortest path is chosen according to an SPR calculation. The two paths go through the two nearest BAN hubs from the source. The nearest BANs from any given source can be found from the source hub-to-connected hub channel gains, approximated from the RSSI at the connected BAN hubs.

The outage probability of CMR is calculated as follows:

$$P_{out} = \left(1 - \left[(1-O_1)(1-O_2)]\right)\left(1 - [(1-O_3)(1-O_4)]\right)\right),$$  \hspace{1cm} (3)$$

where,

$$O_j = O_{j,s}, O_{j,r}, O_{j,d}$$  \hspace{1cm} (4)$$

are the outage probabilities of the route-hops, $j = [1,2,3,4]$; $O_{j,s} = (1 - (1 - O_{j,s})(1 - O_{j,r,d})), i = [1,2]$ and $O_{j,r}$ and $O_{j,d}$ are the individual source-to-relay and relay-to-destination outages, respectively, of each link-hop. The process for CMR is illustrated in Fig. 4 and described with a pseudocode in Algorithm 2.

5 EXPERIMENTALLY-BASED RESULTS

We have considered outage probability and average end-to-end delay as the performance metrics for the experimentally-based optimization techniques in this paper. For estimating the outages properly, the effect of non-recorded measurements (NaN) due to incorrectly decoded packets were replaced with a value of $-101 \text{dBm}$, just below the receiver sensitivity of $-100 \text{dBm}$. 

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**Algorithm 1** Finding shortest path route (with ETX + max. 2 hops count)

1. **procedure** FINDSHORTESTPATH($S$, Path$_{etx}$)
2. $S \leftarrow$ source node
3. $D \leftarrow$ Destination node
4. $P_{etx} \leftarrow$ ETX values of every possible paths from S to D
5. $j \leftarrow$ size of $P_{etx}$
6. for $i \leftarrow 1, j$ do
7. $temp \leftarrow$ Find min ($P_{etx}$)
8. if temp = 2-hop then
9. $S_{to} \leftarrow$ D $\leftarrow$ temp
10. else
11. $P_{etx} \leftarrow$ $P_{etx} - temp$
12. $temp \leftarrow$ Find min ($P_{etx}$)
13. $j \leftarrow j - 1$
14. end if
15. $i \leftarrow i + 1$
16. end for
17. if $S_{to} \leftarrow$ D is empty then
18. $S_{to} \leftarrow$ direct path
19. end if
20. return $S_{to} \leftarrow$ D
21. end procedure

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Fig. 3. Shortest path routing (SPR), with different routing metrics

Fig. 4. Cooperative multi-path routing (CMR) with 3-branch selection combining
5.1 Outage Probability

An estimation of packet error rate and packet delivery ratio, and hence general performance can be made from outage probability, since it is the cumulative distribution function of channel gains. The average outage probability for a network of 10 co-located mobile BANs with shortest path routing (SPR) and cooperative multi-path routing (CMR), is presented in Fig. 5. The outage probabilities are taken from the overall network at assuming different receive sensitivities at a transmit power of 0 dBm.

In Fig. 5 it is shown that, with both SPR and CMR techniques, there is 0% average outage probability for 10 hubs in best-case (at -100 dBm receive sensitivity), indicating a packet error rate close to 0%, which is less than 10%, thus achieving the requirement of the IEEE 802.15.6 Standard. Importantly, they both achieve better than 10% outages at -95 dBm and -88 dBm for SPR and CMR respectively. However, the route found with SPR with respect to ETX metric has only marginally better packet delivery ratio than the SPR method with the combined metric, as it takes the path with lowest cost but can consume more energy with less network lifetime than SPR with (ETX + maximum two hops) due to the length of the route (up to five hops). On the other hand, the route chosen by SPR with respect to the combined metric (ETX + max. two hops) provides a good trade-off between throughput and energy consumption, as it is restricted to two hops. For performing cooperative multi-path routing (CMR), we have also restricted to two route-hops for each path. CMR provides 8 dB performance improvement over SPR with combined metric (ETX + max. 2 hops), at 10% outage probability.

The same process is repeated with transmit power 10 dBm (at hubs) and 5 dBm (at relays) in Fig. 6. The minimum receive sensitivity is considered to be -90 dBm, owing to the increased transmit power and the minimum limit of measured channel gains at -100 dB. For the same reason, the actual receiver sensitivity of the sensors is considered to be -86 dBm for calculating ETX values. By comparing Figs. 5 and 6 it can be seen that, the curves in Fig. 6 shift right with the change of transmit power and receive sensitivity, which implies that, with increased transmit power of on-body nodes, excellent reliability is obtained with less sensitive receivers. In this case, the best-case average outage probability for 10 hubs is also 0% for both SPR and CMR, for receive sensitivities of ≤-88 dBm and ≤-86 dBm, respectively.

5.2 Delay

Delay is an important design and performance characteristic of network. The term delay used throughout this paper is referred to as the end-to-end delay, which specifies how long it takes for a data packet to travel across the entire network.
path from source to destination. End-to-end delay can be roughly estimated as follows:

\[ D_{\text{end-to-end}} = D_{\text{trans}} + D_{\text{queue}} + D_{\text{proc}} + D_{\text{prop}}, \quad (5) \]

where \( D_{\text{trans}}, D_{\text{queue}}, D_{\text{proc}} \) and \( D_{\text{prop}} \) are the transmission, queuing, processing and propagation delays, respectively.

As the processing and propagation delays are negligible in the scenario described in this paper, we have calculated transmission and queuing delays to evaluate the end-to-end delay. The real-time continuous averaged end-to-end delays for the actual dynamic networks consisting of 10 co-located BANs are presented in Fig. 7 according to the IEEE 802.15.6 Standard, latency should be less than 125 ms in medical applications and less than 250 ms in non-medical applications. From Fig. 7 it can be seen that, the averaged delay for 888 continuous time slots, after implementing dynamic shortest path routing (SPR) with respect to (ETX + max. 2 hops) is 76 ms, which is inline with the IEEE 802.15.6 Standard for medical applications.

Also, after applying cooperative multi-path routing (CMR) with 3-branch selection combining, the averaged delay, with respect to (ETX + max. 2 hops) is 129 ms, which also meets the proposed non-medical guideline of 250 ms from the IEEE 802.15.6 Standard. In both cases, the transmit power and receive sensitivity are 0 dBm and −95 dBm, respectively, across all nodes (hubs/relays). It can be noted from the compiled experimental results that, the amount of delay for SPR and CMR remain relatively similar, with the diversion in receive sensitivity (e.g. −100 dBm, −86 dBm) and transmit power (10 dBm at hubs and 5 dBm at relays).

The empirical results found from Figs. 5 to 7 are summarized in Table 1.

### 5.3 Probability Density Functions

We model the combined channel gains acquired after SPR and CMR techniques are applied on the experimentally measured channel gain data. In Figs. 8 and 9 it is shown that the probability density function of the combined channel gains across dynamic SPR and dynamic CMR provide lognormal (Fig. 8) and Weibull (Fig. 9) distribution fits, respectively. The maximum likelihood estimation (MLE) parameter is used to select the best fit. Channel gains are taken over 888 continuous time slots, each of which is for 300 ms.

The probability distribution for the combined channel after applying shortest path routing (SPR) in coexisting BANs is lognormal, which can be calculated from

\[
f(x | \mu, \sigma) = \frac{1}{x \sigma \sqrt{2\pi}} \exp\left(-\frac{(\ln(x) - \mu)^2}{2\sigma^2}\right), \quad x > 0 \quad (6)
\]

where \( \mu = -10.5 \) and \( \sigma = 0.305 \) are the log-mean and log-standard deviation, respectively, for this channel gain fit after SPR is performed.

### Table 1

| Best-case OP with different TP and RS | SPR (ETX + max. 2 hops) | SPR (only ETX) | CMR |
|-------------------------------------|-------------------------|----------------|-----|
| At 10% OP, with TP 0 dBm at hubs and relays, improvement over SPR (ETX + max. 2 hops) | - | 1 dB | 8 dB |
| At 10% OP, with TP 10 dBm at hubs and 5 dBm at relays, improvement over SPR (ETX + max. 2 hops) | - | 1 dB | 6 dB |
| Average end-to-end Delay, with TP 0 dBm at hubs and relays, with −95 dBm RS | 76.3 ms | - | 129.9 ms |
| Average end-to-end Delay, with TP 10 dBm at hubs & 5 dBm at relays, with −86 dBm RS | 76.2 ms | - | 130.9 ms |
The Weibull distribution is commonly used to evaluate the reliability of relayed data. The authors of [33] have shown that the Weibull distribution is the most appropriate distribution for most cases in the pseudo-dynamic situations of BANs. So, the probability distribution for the combined channel gain with cooperative multi-path routing (CMR) in coexisting BANs, can be approximated from the Weibull probability distribution as follows:

\[
f(x | \alpha, \beta) = \frac{\beta}{\alpha} \left(\frac{x}{\alpha}\right)^{\beta-1} \exp\left(-\left(\frac{x}{\alpha}\right)^\beta\right), \quad x > 0
\]

where \( \alpha = 0.00000820 \) and \( \beta = 3.91 \) are the scale and shape parameters, respectively, for the combined channel gain fit after CMR is performed.

6 Conclusion

In this paper, we have proposed cross-layer methods, validated using experimental measurements to optimize radio communication across many co-located wireless body area networks (BANs), by utilizing distinct features at the physical and network layers. Physical layer information (e.g., ETX, hop count) is dynamically fed into the network layer for determining real-time and reliable routes among BAN hubs. We have shown that, in the best-case scenario, shortest path routing (SPR) and cooperative multi-path routing (CMR) provide negligible packet error rate. CMR gives significantly better performance than SPR, by contributing up to 8 dB performance improvement at 10% outage probability, that occurs at practical receive sensitivities for both CMR and SPR. On the other hand, in terms of end-to-end delay, SPR provides a significantly better outcome than CMR, with an averaged delay of 76 ms compared to 129 ms for CMR. The results obtained from the above experiments demonstrate acceptable packet error rate and end-to-end delay across multiple BANs, that meet the IEEE 802.15.6 Standard requirements for a single BAN. We have also observed that, the combined channel gains across a complete SPR route with narrowband communications possess a lognormal distribution, where the complete combined channel gains from CMR have a Weibull distribution. This work provides feasible methods for the deployment of many closely-located BANs in real-world applications with large scale and highly connected healthcare systems.

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