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High Performance Wireless Wearable Technologies for Sports Training and Tele-Health

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Abstract – With the recent advances of technology in wireless communication, sensors, and low power integrated-circuit, Wireless Body Sensor Network (WBSN) has emerged. It has been used in a wide range of applications like healthcare monitoring, sports training, and wellness. However, WBSN poses several issues like scalability, reliability, packet delay due to body blockage, movement and dense deployment. Therefore, an efficient routing scheme is essential to achieve good network performance. This paper presents the performance study of Backpressure Collection Protocol (BCP), a new alternative of data collection protocol that routes packet on a per-packet basis dynamically using congestion gradient, for WBSN. The study consists of evaluating the packet delivery ratio (PDR), packet loss, and end-to-end packet transmission delay for a single-hop and two-hop communication networks using BCP. The experiment results showed BCP performs excellent in WBSN with PDR approximately being 1 and packet loss being zero after 5 seconds booting up, and packet delay on average being 13 milliseconds. The Last-In-First-Out (LIFO) mechanism implemented in BCP appears to be also suitable for health-care monitoring application because the most recent sensing data is sent to base station instead of outdated data. Besides, this paper has demonstrated packet loss optimization to reduce the packet loss during the initial 5 seconds booting to zero packets.

Keywords – wireless body sensor network; wireless wearable technologies; backpressure collection protocol; performance study

1 INTRODUCTION

Wireless Body Sensor Network (WBSN) is a wireless network which consists of collection of sensor nodes on body. The sensor itself is a hardware device capable of monitoring and producing measurable response to a change in physical condition, for example temperature, heart rate. WBSN has a wide range of applications such as in healthcare monitoring, sport training, military, gym and wellness. Figure 1 shows the WBSN and its application. The sensed information from sensor nodes is normally transmitted back to base station either directly in one hop or travelling multiple hops through relay nodes before reaching the base station. After reaching base station, the received information is then visualized, analyzed and acted upon. Regardless of their numerous applications, wireless sensor network poses several issues like energy efficient, reliability, scalability, interference, congestion control, and response time. These issues are due to the intrinsic features of sensor nodes that have tightly limited power supply, computational capability and available bandwidth. Besides, the process of forming a path from one node to the other nodes crossing one or more relay nodes, called routing also plays an important role in communication. When a packet arrives, a node needs to decide and route the packet to the base station efficiently. Otherwise, unbalanced task allocation in wireless sensor network where some nodes are over-loading and others are under-loading will occur. Consequently, there is a need to adapt the networking process to deliver and match the application requirements while minimize the resources consumed and extend the life of the network to give good throughput. Distributing the workload across the sensor nodes to optimize the resource use, maximize throughput, minimize delay and avoid overload of any sensor nodes have become major challenge.

In this research, Backpressure routing – an alternative approach of Minimum Cost Routing Trees approach in data collection protocol is explored. Backpressure Collection Protocol (BCP) is tested on TelosB motes with two network setup, single-hop communication and two-hop communication network. It is found that BCP works great for light load (small number of nodes) static and mobile nodes in WBSN. Several data collection protocols will be reviewed in Section 3. In Section 4, description and implementation of Backpressure Collection Protocol (BCP) are discussed. Section 5 presents the performance study of BCP in terms of packet delivery ratio, packet loss and end-to-end delay for single-hop and two-hop communication networks. Moreover, improvement in packet loss performance is conducted. Finally, conclusion is described in Section 6.

2 OBJECTIVE

The main objective of this research is to understand the design concept and implementation of Backpressure Collection Protocol in TinyOS, study Backpressure Collection Protocol’s network performance for wireless body sensor network and thus, suggest and perform
optimization of existing Backpressure Collection Protocol model to improve the network performance and resource utilization.

Figure 1 Wireless Body Sensor Network and Its Application

3 LITERATURE REVIEW

Research activities on Wireless Body Sensor Networks (WBSN) have been done intensively over the past few years. In most WBSN applications, besides generate and propagate their own information, sensor nodes also serve as relays to forward packet to other nodes. Design of a routing protocol is challenging due to characteristics of WBSN like body blockage, frequent dynamic changes (topology changes due to node failures), and unreliability of the wireless link [7]. An effective routing protocol is significant. A number of data collection protocols have been developed for wireless sensor network. Each of them has different pros and cons. In this section, several routing protocols are discussed.

3.1 ARBUTUS

Arbutus is a routing architecture that seeks to achieve high reliability and maximize the good put given the reliability constraint by routing over a few long hops instead of many short hops [1]. The distance of hop whether long or short does not affect the transmit power which is assumed to be the same. Arbutus is a cost-based routing, the cost of reaching the destination is estimated by each node locally. Routing scheme is collection tree (any to one or many-to-few), while protocol is sender-based, in which nodes unicast packets to their specific parents.

3.2 MULTI-CHANNEL COLLECTION (MCC)

MCC is a protocol that uses high-rate multi-channel in a time-scheduled manner for fair, real-time data collection in wireless sensor networks [8]. MCC incorporates mechanism for balanced routing tree formation, multiple frequency channel allocation and globally synchronized TDMA scheduling. In data collection, MCC can achieve close to maximum possible network throughput with very low synchronization overhead. MCC allows real-time and fair data collection from all sensors instead of bulk data transfer from one or two sensors at a time compared to PIP (Packets in Pipe).

3.3 COLLECTION TREE PROTOCOL (CTP)

Reference [9] presents CTP, a tree-based collection protocol that computes routes to one or more sink. Every node builds and maintains minimum cost tree with the sink as root. CTP uses ETX (Expected Transmission) as its routing gradient and it chooses the lowest ETX value. CTP provides efficient, robust and reliable routing. It has been widely used and deployed in Tiny OS as “best-effort” anycast datagram communication. The disadvantages of CTP are routing loop and packet duplication problem. Besides, CTP does not consider load balancing issues, it only targets at reducing the packet delivery cost.

3.4 BACKPRESSURE BASED ROUTING

The principle behind backpressure routing is to route traffic using congestion gradients dynamically over a multi-hop network. It operates in slotted time. At each time slot, packet data are routed in directions where differential backlog between neighboring nodes is maximized. Advantages of using backpressure algorithm are maximum network throughput, able to implement without knowing the channel state or traffic arrival rates, robust to time-varying network conditions. Disadvantages of backpressure algorithm are large delays and hard to implement in networks with interference. Several backpressure-based routing are discussed below. Backpressure Collection Protocol will be discussed further in section 4.

3.4.1 Backpressure-Based Rate Control

Backpressure-based rate-control protocol is a protocol implemented in two parts, a flow controller and a backpressure based scheduler [4]. The rate of packet injecting into network is determined by flow controller module. While the minimization of the overall queue size in the network is done by backpressure based scheduler by scheduling node transmissions based on node queue differential. It has showed that the settings of backpressure protocol parameters are dependent of current traffic condition and must allow automatic parameter adaptation.

3.4.2 Backpressure with Adaptive Redundancy (BWAR)

Reference [3] presents the problem in Backpressure-based protocol that when queues are short or low in traffic load, it will result in long delays. For this type of network, it has been proposed to use redundant transmission to reduce delay, however it will also increase delay dramatically in high traffic load. To overcome these issues, the authors propose to use Backpressure with Adaptive Redundancy to improve the throughput and delay. At low traffic load, BWAR duplicates copies of packets in a new duplicate buffer.
When the original queue is empty, the duplicate packets will get transmitted. Duplicate packet is removed using timeout mechanism. At low load, BWAR outperforms traditional backpressure. At high load, BWAR outperforms Spray and Wait.

3.4.3 Diversity Backpressure Routing with Mutual Information Accumulation

Reference [2] presents DIVBAR-MIA, a modification of Diversity Backpressure algorithm in which packet with the largest backpressure will be transmitted and forwarded using the link with the largest queue length. It also retains the partial information accumulated at the receivers until corresponding packet is delivered to the destination. The retained partial information can facilitate the decoding in the future transmission attempts. DIVBAR-MIA improves the throughput performance of the original DIVBAR.

3.4.4 Augmenting the BCP to Support Multiple Sink

Reference [6] presents an enhancement of BCP to route packets to multiple sinks within a network. The authors studied the design on BCP with the expectation to reduce the memory overhead, improve packet delivery performance and adherence to conditions imposed by backpressure routing. 3 possible solutions suggested by the authors include virtualization of queue management, clustering of network and feedback based model. The disadvantages of using virtualization of queue management are packet header and storage of local backpressure to sinks will increase with the increase number of sinks. While in using the clustering of network if there is no controlled broadcasting until packets reach a node in the desired cluster of a sink, then undesirable redundancy of messages will increase. In feedback based model where nodes choose their next hop based on feedback and past performance, new weight parameter (feedback) needs to be considered to calculate the weight and convergence of the entire network takes more time in case of mobile sinks.

Table 1 shows the summary of routing protocols that have been reviewed. Remark column defines the effect if the routing protocol is being deployed in WBSN network.

Based on the table 1 Summary of Routing Protocol and analysis of different protocol in Section 3.4 for WBSN and BCP in Section 4, Backpressure-based routing protocol may be more viable for evaluating its performance and effectiveness in WBSN.

4 WIRELESS PROTOCOL – BACKPRESSURE COLLECTION PROTOCOL

Reference [5] presents Backpressure Collection Protocol (BCP), a low-overhead dynamic backpressure routing in wireless networks which is implemented to address the concerns about large packet delays, scalability, packet looping, and the effect of link losses in practical systems that are based on backpressure routing. BCP route and forward packet independently on per-packet basis using information about backpressure weight and link states.

<table>
<thead>
<tr>
<th>Method</th>
<th>Effectiveness</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arbitration</td>
<td>30% reduction in network traffic load.</td>
<td>Better load balancing</td>
<td>High overhead</td>
<td></td>
</tr>
<tr>
<td>Forward packet</td>
<td>Topology aware CTP. Arbiter have</td>
<td>Better load balancing</td>
<td>Some overhead</td>
<td></td>
</tr>
<tr>
<td>Diversification</td>
<td>− 30% improvement CTP’s successful delivery attempts</td>
<td>Significant improvement for load balancing mechanisms</td>
<td>Increased latency</td>
<td></td>
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<td>Better load balancing</td>
<td>Some overhead</td>
<td></td>
</tr>
</tbody>
</table>

4.1 WEIGHTAGE CALCULATION

Equation (1) shows the calculation of backpressure weight that performs by each node for making routing decision and forwarding decision. Node $\alpha$ calculates backpressure weight ($W_{\alpha,\beta}$) for its entire neighbor node $\beta$. $Q_{\alpha,\beta}$ is the queue differential or backlog of node $\alpha$ minus node $\beta$, $C$ is constant that trades system queue occupancy for penalty minimization, $ETX_{\alpha,\beta}$ is link usage penalty, and $R_{\alpha,\beta}$ is the estimated link rate. The link with the highest $W_{\alpha,\beta}$ value means nodes j is the next hop for the packet.

$$W_{\alpha,\beta} = Q_{\alpha,\beta} - C \cdot ETX_{\alpha,\beta} \cdot R_{\alpha,\beta}$$

4.2 LAST-IN-FIRST-OUT MECHANISM AND FLOATING QUEUE

In BCP, traditional First-In-First-Out (FIFO) queue service is replaced with Last-In-First-Out (LIFO) queue. The LIFO queue mechanism is capable to decline the average packet delivery delay drastically because new packet generated will be rapidly sped to destination. Besides, BCP uses floating queues to improve backpressure scalability.

Fig. 2 illustrates LIFO mechanisms and forwarding decision based on backpressure weight. At time B, three packets (Solid Square) intended for sink nodes (S) are
injected at nodes 1 and nodes 2 and causes $W_{2,1}$ and $W_{1,2} > 0$, respectively. Node 2 then forwards a packet to node 3 and node 1 sends a packet to node sink.

### 5 PERFORMANCE STUDY

Radio channel is the communication medium among nodes in WBSN. To analyze the performance of Backpressure Collection Protocol, several experiments are conducted.

#### 5.1 PERFORMANCE METRIC

The performance metric uses in the experiment to evaluate the Backpressure Collection Protocol’s performance are as follows.

##### 5.1.1 Packet Loss

Packet loss is defined as the total number of packets loss or the difference between generated packet and received packet (2). The performance of protocol is better with lower value of packet loss.

$$\text{Packet Loss} = \text{Sent Packet} - \text{Received Packet} \quad (2)$$

##### 5.1.2 Packet Delivery Ratio (PDR)

The performance metric that illustrates the level of sent packet to base station is packet delivery ratio. It is the ratio of the number of packets acknowledged by base station over the total number of packets transmitted by transmitter (3). Higher packet delivery ratio means the better the protocol’s performance.

$$\text{PDR} = \frac{\text{Received Packet}}{\text{Sent Packet}} \quad (3)$$

##### 5.1.3 End-to-End Delay

The average time taken by a packet successfully delivered from transmitter to receiver is defined as end-to-end delay (4). It also includes the delay of a packet reside in one node’s queue for data packet transmission and route discovery process. Protocol performance is better with lower value of packet delay.

$$\text{Delay} = (\text{Arrive Time} - \text{Send Time}) \quad (4)$$

### 5.2 EXPERIMENT

Crossbow’s TelosB motes (TPR2400) based on IEEE 802.15.4 radio with integrated antenna is used in these experiments. The TelosB runs TinyOS 2.x, an open source, free component based operating system written in nesC programming, and it is used for developing low power application like WBSN. Two network scenarios is conducted: single transmitter and receiver (single hop communication) and single transmitter, forwarder/relay and receiver (two hop communication).

#### 5.2.1 Single Transmitter and Receiver

Fig. 3 shows the simplest scenario where it consists of two nodes. Node 0 serves as a receiver/base station and node 1 serves as a transmitter. Packet size is 5 bytes and data rate are 5, 10, and 20 packets per seconds (pps).

![Figure 3 Single Hop Communication](image)

In Fig. 4, the packet loss for 10 pps and 20 pps sending rate, sending from node 1 to node 0 is shown. At 5th seconds, the total packet loss for 10 pps sending rate is approximately 35 packets, while the total packet loss for 20 pps sending rate is approximately 92 packets. In the first 5 seconds, transmitter is not receiving backpressure information from receiver (nodes broadcast beacon containing backpressure information every 5 seconds). As a result, the packets generated during this period will be dropped because stack (send queue) which is capped at maximum 12 packets per nodes is overflow. The number of dropped packet depends on the time when transmitter receives beacon from other nodes after boots up and source sending rate. The dropped packet will be those generated at early stage due to LIFO stack mechanism. After 5 seconds, transmitter will send packet to receiver with zero packet loss. The maximum sending rate for zero packet loss, after the first 5 seconds upon power on (in stable condition) is below 50 packets per seconds sending rate.

#### 5.2.1.1 Packet Loss

In Fig. 5, the PDR for 10 pps and 20 pps sending from node 1 to node 0 is shown. At 5th seconds, the total packet loss for 10 pps sending rate is approximately 35 packets, while the total packet loss for 20 pps sending rate is approximately 92 packets. In the first 5 seconds, transmitter is not receiving backpressure information from receiver (nodes broadcast beacon containing backpressure information every 5 seconds). As a result, the packets generated during this period will be dropped because stack (send queue) which is capped at maximum 12 packets per nodes is overflow. The number of dropped packet depends on the time when transmitter receives beacon from other nodes after boots up and source sending rate. The dropped packet will be those generated at early stage due to LIFO stack mechanism. After 5 seconds, transmitter will send packet to receiver with zero packet loss. The maximum sending rate for zero packet loss, after the first 5 seconds upon power on (in stable condition) is below 50 packets per seconds sending rate.

#### 5.2.1.2 Packet Delivery Ratio

Fig. 5 shows the PDR for 10 pps and 20 pps sending from node 1 to node 0. PDR for 10 pps and 20 pps sending rate is equal to 1 approximately after 5-8 seconds.

#### 5.2.1.3 End-to-End Delay

Table 2 shows that the delay experienced by each packet is different. The packet delay for 10 pps and 20 pps sending rate is around 13 milliseconds on average. The packets which reside at the stack during the initial 5
seconds interval (before receiving beacon from other nodes) will experience higher end-to-end packet delay.

**Figure 5 Packet Delivery Ratio (Single-Hop Communication)**

**Table 2 End-to-End Delay (10 pps and 20 pps)**

<table>
<thead>
<tr>
<th>Packet Delay (ms)</th>
<th>Number of Pkt</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>54</td>
<td>0.08557847</td>
</tr>
<tr>
<td>13</td>
<td>563</td>
<td>0.89540412</td>
</tr>
<tr>
<td>22</td>
<td>1</td>
<td>0.001584786</td>
</tr>
<tr>
<td>32</td>
<td>1</td>
<td>0.001584786</td>
</tr>
<tr>
<td>34</td>
<td>1</td>
<td>0.001584786</td>
</tr>
<tr>
<td>52</td>
<td>1</td>
<td>0.001584786</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>0.001584786</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>0.001584786</td>
</tr>
<tr>
<td>44</td>
<td>1</td>
<td>0.001584786</td>
</tr>
<tr>
<td>55</td>
<td>1</td>
<td>0.001584786</td>
</tr>
<tr>
<td>500</td>
<td>1</td>
<td>0.001584786</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>0.001584786</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>0.001584786</td>
</tr>
</tbody>
</table>

**Figure 6 Two-Hop Communication**

In Fig. 6, node 2 is placed away from base station’s coverage area such that it is unable to send packet directly to base station, while node 1 is placed between base station and transmitter. When node 1 receives packet (with destination to base station) from node 2, it will forward / relay it to base station. Similar to single-hop communication, the packet size is 5 bytes and sending rate are 10 pps and 20 pps. Booting up forwarder and transmitter node slightly 3 to 4 seconds after booting up base station has been tried as well in this experiment. It results in better performance: less packet loss, better PDR and shorter end-to-end transmission delay.

**Figure 7 Packet Loss for 10 pps (Two-Hop Communication)**

**Figure 8 Packet Delivery Ratio for 10 pps (Two-Hop Communication)**

**Table 3 End-to-End Delay for 10pps (Two-Hop Communication)**

<table>
<thead>
<tr>
<th>Rate</th>
<th>Node</th>
<th>Min Delay</th>
<th>Max Delay</th>
<th>Avg</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 pps</td>
<td>Transmitter</td>
<td>30 ms</td>
<td>1642 ms</td>
<td>31 ms</td>
</tr>
<tr>
<td></td>
<td>Forwarder</td>
<td>12 ms</td>
<td>864 ms</td>
<td>13 ms</td>
</tr>
</tbody>
</table>

**Performance** - Packet loss is depends on the source sending rate and the time interval between when transmitter boots up and when it receives beacon from base station. For example, if the transmitter sends at 10 packets per seconds (pps), the packet loss for the first 5 seconds (the worst case of interval) will be about 50 packets minus of the maximum stack 12 packets. With the setting of different boots up timing mentioned earlier, Fig. 7 shows the packet loss for 10 pps. For 10 pps sending rate from both forwarder and transmitter to base station, the packet loss is 2 packets and 3 packets. For 20 pps sending rate, the packet loss is 5 and 8 packets. Fig. 8 shows the PDR for 10 pps in two-hop communication is approximately 1, similarly for 20 pps. Table 3 shows the end-to-end packet transmission delay for 10 pps. On average, transmitter’s packet will arrive at base station after 31 milliseconds and forwarder’s packet after 13 milliseconds. Transmitter’s packet experience more delay than forwarder’s packet because of waiting time in forwarder’s queue.
5.2.2.2 Different Forwarder’s Sending Rate and Transmitter’s Sending Rate

Different from Section 5.2.2.1, in this experiment, node 1 which acts as a forwarder to relay packet is set to higher sending rate (20pps) than transmitter/node 2 (10pps). It is observed that there is no packet loss at node 2 even though sending rate of node 1 is much higher than node 2. Because, there is no priority allocation in the node 1’s sending queue (stack). All packets generated by node 1 or node 2 respectively will be put in the same queue (sending queue) based on the time they arrived. In a multi-nodes communication setup where all nodes are scattered, each packet will experience different hop count to arrive to base station.

5.3 OPTIMISE PACKET LOSS

In Section 5.2.1 and 5.2.2, it is observed that packet is mostly lost during the interval of node boots up to node receives beacon containing backpressure information from other nodes. The higher the source sending rate or/and the longer the time interval, the higher the number of packet loss. There are two ways to avoid packet loss during this interval when acquiring critical sensing data. Firstly, it is suggested to start capture data after 5 to 10 seconds of initial boot up which might be achieved at application layer. Secondly, it is suggested to start sending packet after receiving beacon from other nodes.

![Packet Loss Optimization](image)

Figure 9 Packet Loss Optimization

The second suggestion has been implemented on existing backpressure collection protocol by modifying the code to allow transmitter to start to send packet only if it has received beacon from other nodes or base station. From the Fig. 9 plots of packet loss for 10 pps and 20 pps sending rate, it is observed that 10 pps and 20 pps sending rate has zero packet loss at 5th seconds. Therefore, the total packet loss for all time is zero.

6 CONCLUSION

The performance of Backpressure Collection Protocol (BCP) in Wireless Body Sensor Network (WBSN) is presented in this paper. In Section 5.2, packet delivery ratio, packet loss and packet transmission delay performance are evaluated for single-hop and two-hop communication network. Packet loss occurs during the interval time when transmitter does not receive backpressure information from other nodes only. Thereafter, transmitter will not experience packet loss and have PDR equal to 1, while packet delay on average is 13 milliseconds. These results show that BCP is an efficient routing scheme for WBSN in terms of packet delay and reliability. To overcome the packet loss during that interval, optimization is done in Section 5.3 by starting to transmitting packet only after receiving backpressure information. In future work, we would like to evaluate the power consumption, simulating sending variable packet size of data with realistic movement using BCP in order to obtain greater understanding of its performance and influence.

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