Energy Efficient Multichannel Cross-Layer Routing Protocol for Internet of Things Applications

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***Abstract*— Wireless Sensor Networks are ad-hoc networks that consist of low-power sensor nodes connecting to the Internet through a sink or low power border router. The channels that these low-power radios used often suffer from interference from the other devices sharing the same frequency. Multichannel protocol in wireless networks is one of the most studied solutions to mitigate the effects of interference to enable the network to operate reliably. However, the process of selecting a suitable channel could lead to higher energy consumption which is not ideal for sensor nodes. This paper shows the estimation of the energy consumption computation and its implementation in Multichannel Cross-Layer Routing Protocol (MCRP). MCRP helps to minimise the number of packet retransmissions, thus improves the node's energy efficiency as less energy is consumed. The energy consumption in MCRP is evaluated based on the packet transmission and packet forwarding energy. It can be concluded from the results that MCRP, which is a multichannel protocol, consumes less energy compared to a single-channel protocol in the situation where there is high interference present.**

Keywords—Wireless Sensor Networks, WSN, multichannel protocol, energy estimation

I. INTRODUCTION

Wireless Sensor Networks (WSN) consists of sensor nodes that typically use low-power radios and are mainly powered by batteries. While sensor nodes have the advantage of the ability to be deployed in various locations and situations, the energy consumption and lifetime of the nodes is one of the concerns that need to be addressed. There have been various studies to estimate the node's energy consumption in real-time through MAC and routing protocols to reduce the energy waste, thus making it more energy efficient. In MAC protocols, the radio duty cycle is exploited to find the optimal value for the nodes to be awake efficiently, for transmission or reception without wasting energy idling. In terms of the routing protocols, fairly distributed nodes' load among the nodes and routes helps to balance out the communication from overloading certain nodes. Normally, nodes that are closer to the sink are the most constrained as they have more traffic to forward, thus, more bandwidth and energy are consumed compared to the other nodes. Another important factor that affects the energy consumption that has been extensively studied is the condition of the radio link. Multichannel protocol considers the use of different channels within the frequency spectrum to avoid channels that have high interference from other devices. As the result, the nodes' energy efficiency can be improved as multichannel can ensure minimal packet retransmissions, thus reducing energy consumption if it is done properly.

Multichannel Cross-Layer Routing Protocol (MCRP) is a decentralised cross-layer protocol with a centralised controller that can mitigate the effect of interference. MCRP does not require any knowledge of the channels' occupancy at any location. This generality enables the sensor nodes to select the most suitable channel based on the current channel condition at the specific location where the nodes are deployed. The initial version of MCRP can be referred to in the conference paper [1] that presented the simulation results. It showed that MCRP reduced the loss rate at approximately 99%. This paper describes the implementation of energy consumption computation using Contiki's existing energy estimation module in MCRP to evaluate the effectiveness of multi-channels in terms of energy usage.

II. REAL TIME ENERGY ESTIMATION

MCRP is implemented in Contiki [2], which is an open-source operating system for WSNs. Contiki provides an energy estimation module called *energest*. The way that *energest* works is by keeping track of the radio start and stops time (duty-cycle) for per-component energy or power consumption in real-time during transmit, receive, low power, and full power modes. *Energest* measures the estimated energy in a particular state. The *Powertrace* system [3] is a software-based power state tracking system at the network level in WSNs. It profiles the power behaviour and computes the estimation of the power consumption at run time per-activity power cost, such as the different states for wakeups, transmissions, and receptions of a node. Compared to the oscilloscope energy measurements, *Powertrace* has an accuracy of 94%. *Energest* is used by *Powertrace* to reduce the period of radio activity in the specific state to calculate the average energy or power consumption.

Powertrace uses the software-based on-line energy estimation mechanism [4] that is also implemented in Contiki, to estimate the node's current energy consumption in real-time. The energy estimation module uses time measurements that can be directly obtained from the microprocessor on-chip timer when the component is switched on to produce a time stamp. The time difference from when the component was on and when it was later switched off is computed to estimate the energy consumed when the node is transmitting, receiving or in idle mode.

$$\frac{E}{V} = I_m t_m + I_l t_l + I_{tx} t_{tx} + \sum_i I_{c_i} t_{c_i} \quad (1)$$

$$E = (1.8t_m + 0.0545t_l + 19.5t_{tx} + 21.8t_r)\left(\frac{3}{32768}\right) \quad (2)$$

Equation (1) shows the energy consumption model [4], *E*, supply voltage *V*, current draw *I*, and active time *t*, computed in *Powertrace* for microprocessor *m*, microprocessor in low power mode *l*, communication device in transmit mode *tx*, communication device in receive mode *r*, and other components c_i, such as sensors and LEDs. I_m, I_l, I_{tx} and I_r values are device dependent. Throughout this paper, (2) is used where the total energy *E* is calculated in *mJ*, the current in *mA* and the on-chip timer default value is 32768*Hz* for one second runtime on a 3*V* sensor. TelosB datasheet [5] is referred to obtain the values of the components used in the equation.

III. MCRP ENERGY ESTIMATION IMPLEMENTATION

In WSNs, the nodes typically do not have enough capability to compute their energy consumption as the nodes are battery powered. To estimate the energy consumption of the node, each node sends their *energest* values of the packet transmission, packet forwarding, and total time value that the radio has been on from the beginning, to the Low Power Border Router (LPBR) regularly. LPBR is the centralised controller for MCRP, that has more RAM and better processing capabilities than sensor nodes. The nodes' knowledge of their energy level is kept at a minimum as the information is known by the LPBR to compute and predict the energy drain for all nodes if the routes have high interference or packet losses. Based on the *energest* values provided by the nodes, LPBR can compute the energy consumption on each route and the nodes' estimated battery level.

To accurately calculate the energy consumption of the transmitted packets, the unicast packet type is separated into two; normal unicast and control messages unicast. A normal unicast packet that is received from the application layer is set as *unicastMsg = 1*, while the default value of 0, *unicastMsg = 0* represents the control messages unicast. By doing this, periodic control messages energy can be excluded from the total transmission energy, as the main concern of energy consumption is in terms of the transmission and retransmissions of the normal packets. This will alert the LPBR of any peak in the energy consumption that might happen due to retransmissions, not because control messages are being sent periodically. The *unicastMsg* value is reset when the link-layer acknowledgement is received or the maximum number of retransmissions is reached.

Fig. 1 shows the implemented energy consumption pseudo-code in MCRP to compute the transmission energy, forwarding energy and the packet's total energy. Before the energy consumption of the sender to the receiver is calculated, the end-to-end routes taken by the node are checked each time to ensure that the routes have not changed. If the routes have changed, the end-to-end route information will be updated. The sender node checks the next hop node to keep track of the forwarding energy, *fwdE* as part of the packet's energy consumption. If the next hop node is the LPBR, there is no forwarding energy. Otherwise, the next hops are included until the packet reaches LPBR and the total energy consumption of the packet, *totalE* can be computed. It includes the transmission energy *txE* and the forwarding energy *fwdE* from the intermediate nodes.

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Notations
R is a node that is a Route
txE is the transmission period
fwdE is the forwarding period
totalE is the total run time

Pseudo-code
Generate the end-to-end routes taken by the node
if next hop node = R then
  | R is node's next hop
  | Check R next hop
  | if R = LPBR then
  |   | All end-to-end routes found
  |   | Access energy table node txE, R fwdE
  |   | Compute energy consumption using Equation
  | end
else
  | Check R next hop R
  | Update the routes
end
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Fig. 1. Pseudo-code of energy consumption in MCRP

IV. ENERGY ESTIMATION EVALUATION

MCRP is evaluated in the Cooja [6] simulated environment with emulation of TelosB nodes that feature the CC2420 transceiver, a 802.15.4 radio. The nodes run on IPv6, using UDP with standard RPL and 6LoWPAN protocols. Fig. 2 shows the network layout of the simulation nodes. The network consists of 31 nodes; 1 border router (LPBR) node, 16 interference nodes, and 14 UDP clients of duty-cycled nodes that send packets to the LPBR. These nodes spanned over 20-30 metres between the closest node. The border router, which is a PC is used as the LPBR to allow most processing decisions to be done without limitation, as it has more RAM and better processing capabilities than a sensor. A TelosB sensor has limited RAM and ROM of 10K bytes and 48K bytes of flash memory [5]. By using a border router, MCRP's decisions on channel switching can be moved to the LPBR instead of on the sensors. This allows real-time channel switching decisions, without draining the memory and battery on a sensor. The border router also acts as the root of the tree.

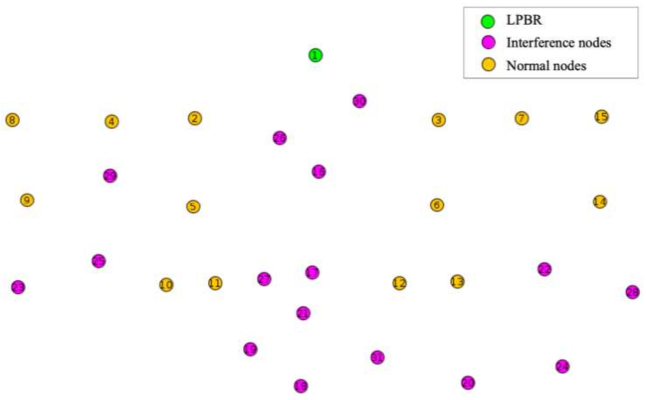

Fig. 2. Layout of the simulation nodes

MCRP performance is tested in various conditions of degraded channels to better understand the performance of the protocol, through the use of controlled interference nodes. The interference nodes generate semi-periodic bursty interference that is simulated to resemble a simplified Wi-Fi or Bluetooth transmitter on several channels at random. The interference model proposed in [7] is used in the simulation to generate a similar packet loss rate to the values of the theoretical and real nodes given in [8]. The interference model does not fully mimic the real-world interference behaviour; however, it can be used to predict the performance of MCRP in worse case scenarios. In the extreme interference case, the interference happens between 0.14 to 0.23 seconds, with a clear time of between 0.18 to 0.31 seconds for transmissions while the moderate interference is 0.28 to 0.47 seconds with a clear time of 0.38 to 0.63 seconds.

The energy consumption in MCRP which is a multichannel protocol and single-channel protocol, are computed and compared in terms of the transmission per packet, the forwarding packet and the total energy used, to prove that multichannel protocol can prolong the network lifetime as it uses the energy more efficiently. In the simulation, 350 packets are sent throughout the simulation period, where each node sends one packet per minute. The nodes' energy consumption is calculated using Equation (2). As the nodes are battery powered and have limited energy, LPBR computes the energy consumption of each node based on the information contained in the transmitted packet. Node with the ID 2, 5 and 15 energy usages are selected for comparisons as other nodes show a similar result. Node 2 is one-hop to the LPBR while node 5 is two-hop and node 15 is three-hop away. The maximum number of hops in the simulation is three hops. The result of a single channel protocol with no interference is used as the base case as it is the ideal energy consumption value. The results of MCRP as the multichannel protocol are compared to the energy of a single-channel protocol with moderate and extreme interference.

A. Energy Per Packet Performance

Fig. 3-5 shows the transmission energy per packet for one, two and three-hop nodes. Based on the Fig.s, it can be seen that the transmission energy per packet for nodes that are further away from the LPBR is higher as it requires more hops. One-hop nodes consume the least transmission energy as the nodes are in direct access to the LPBR. In this simulation, the maximum number of hops is three. In a large-scale network, the number of hops cannot be reduced as not all nodes would be in the range or directly connected to the destination node. Thus, the node's next hop should be selected carefully to avoid nodes that are on the higher interference channel.

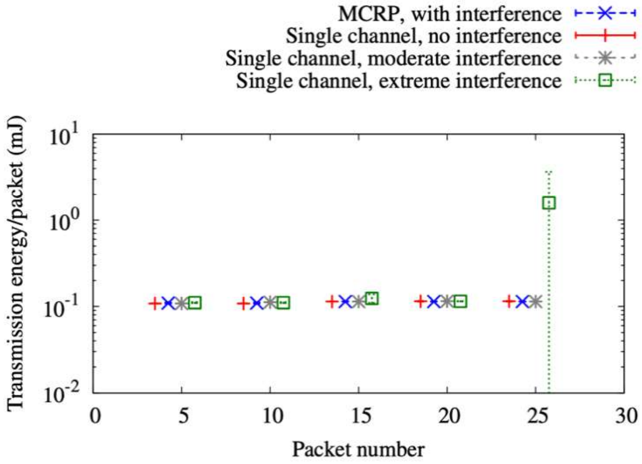

Fig. 3. Energy consumption per packet for one-hop nodes

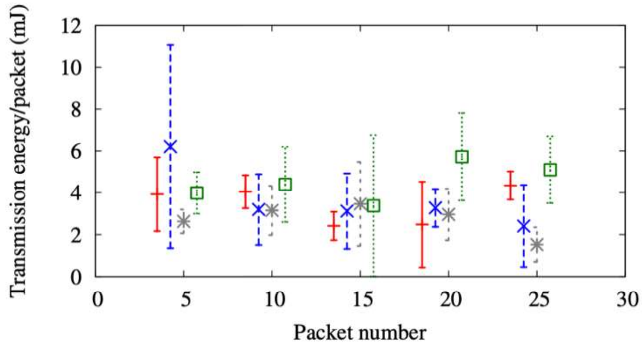

Fig. 4. Energy consumption per packet for two-hop nodes

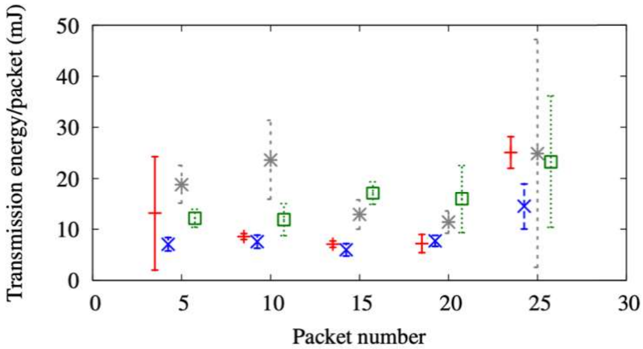

Fig. 5. Energy consumption per packet for three-hop nodes

In Fig. 3, the one-hop node's energy consumption for the 5th, 10th, 15th, 20th and 25th packet is approximately similar in all cases. As it is one-hop to the destination (LPBR), the nodes were not badly affected by the interference as the nodes are able to send the packets when their channels are clear as LPBR is always listening for any incoming packets. There is a slight variation in the single-channel protocol with extreme interference case for packet 25. Fig. 4 and Fig. 5 show higher packet transmission energy consumption from the senders to the LPBR through two and three-hop. This is because of the interference that occurs on the nodes' channels. The nodes are unable to detect the exact wake-up time to sync with the intermediate nodes, thus, the nodes have to transmit in a longer period to ensure the packet gets transmitted. In the one-hop graph, the energy can be kept at a minimum because the

LPBR is always awake to accept the packet as it is fully powered unlike the other nodes that are battery-powered. Those nodes have to save energy by switching the radio off when there are no transmissions and receptions taking place. In both graphs, MCRP shows approximately similar transmission energy consumption to the single channel without interference case. The transmission energy for a single-channel protocol with moderate and extreme interference is slightly higher compared to MCRP in two-hop. In three-hop, the energy per packet in the single channel protocol with moderate and extreme interference are much higher than the energy used by the single-channel no interference case and MCRP. This shows that the energy per packet depends on the number of hops and the interference that affects the routes. The multichannel protocol helps to mitigate the effect of interference, thus reducing the transmission energy taken to send a packet.

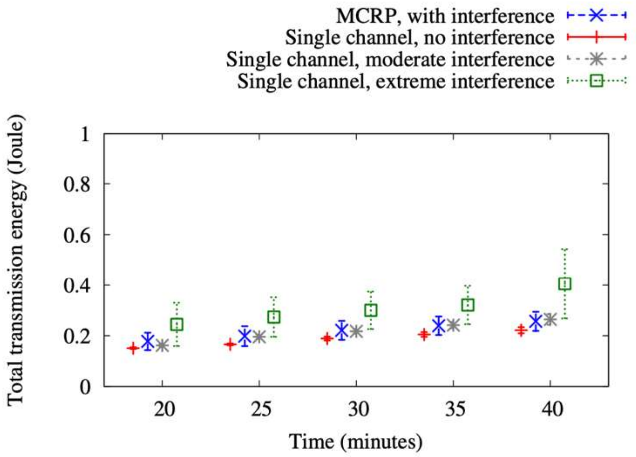

Fig. 6. Total energy consumption per packet for one-hop nodes

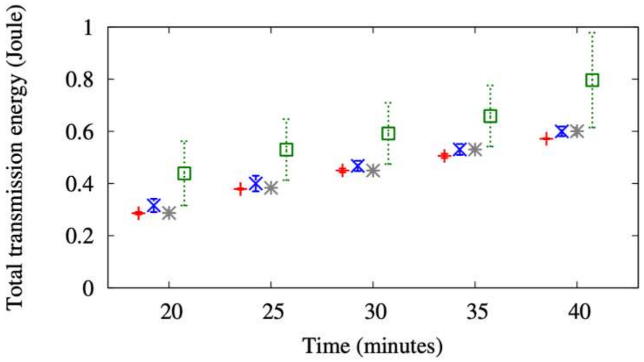

Fig. 7. Total energy consumption per packet for two-hop nodes

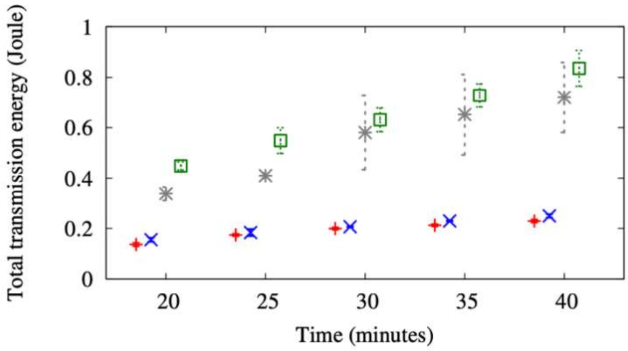

Fig. 8. Total energy consumption per packet for three-hop nodes

B. *Energy Over Time Performance*

Fig. 6-8 shows the graphs of the one, two and three-hop nodes' total energy consumption in approximately 40 minutes to send 25 packets that include the retransmissions and control packets' energy. This improvement can be seen in Fig. 7 where even though the transmission energy increases over time due to interference which resulted in more retransmissions, compared to a single-channel with extreme interference, MCRP managed to minimise the total energy consumption to match the energy used by single-channel with moderate interference. If the retransmissions fail, the packet is dropped, and the energy used during the retransmissions is wasted. The total energy consumption graphs show all energy from the packet transmission including the failed packet's energy.

Fig. 6 shows the one-hop node's energy consumption. The total energy taken is approximately similar in MCRP and single channel with no and moderate interference, with a small increase over time. The single-channel protocol with extreme interference cases, however, consumed higher total transmission energy than in other cases. This is because packet transmission and retransmissions can only occur within a limited time frame as the channel is normally busy. This could overload and risk the packets to get dropped even though LPBR's radio is always on and ready to receive the packets. Fig. 7 shows a higher increase in energy usage over time in all cases. The reason for this is because two-hop nodes have two other nodes that are using it as a forwarder. The forwarding energy is included within the total transmission energy of the node. Two-hop nodes use higher energy when forwarding packets to the LPBR compared to the one-hop node. Fig. 8 has lower energy consumption as three-hop nodes do not act as a forwarder, unlike the two-hop nodes.

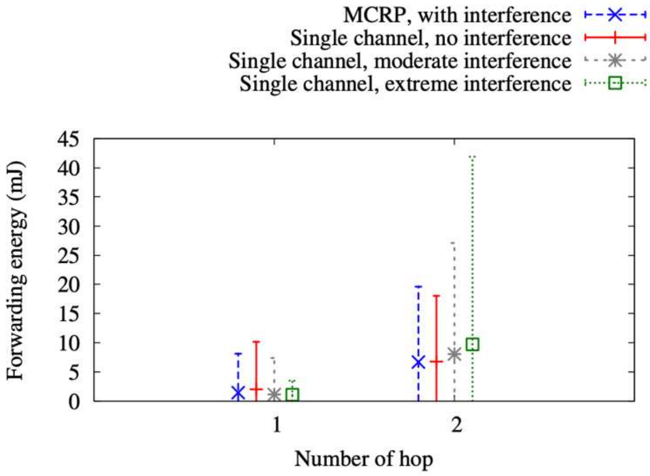

Fig. 9. The forwarding energy of one and two-hop nodes

C. Forwarding Energy Performance

In terms of the energy used to forward packets, only the energy from one and two-hop nodes are measured. This is because the three-hop nodes do not forward packets but instead, sending them to the intermediate nodes. Fig. 9 shows the forwarding energy consumed by the nodes, where it can be seen that one-hop nodes use less energy compared to the two-hop nodes as the nodes only need to check the availability of the channel to be used for transmission before it can forward packets to the LPBR. As the LPBR is fully powered, the LPBR radio is always on and ready to receive the incoming packet, thus reducing the nodes' waiting time. Nodes that are forwarding the packets to the intermediate nodes have to be awake for a longer time to sync and ensure that the intermediate nodes are also awake and ready to receive the packets. Thus, if the nodes could not sync or wake up at different times, energy consumption during packet forwarding could be higher than an end-to-end packet transmission. In the simulation, there is a limited number of forwarding nodes. In larger networks with an increased number of nodes, more energy will be spent on packet forwarding as there might be more hops to get to the LPBR. The forwarding energy consumption contributes to the most energy used by the nodes. Even though MCRP does not show a lot of improvement in terms of the forwarding energy, it shows a lower deviation compared to the single-channel protocol with extreme interference.

V. CONCLUSIONS

This paper presents the estimated energy consumption computation using *Powertrace* in Contiki. MCRP measures the estimated energy consumption using *Powertrace* that tracks the duty cycle values. Based on the simulation result, it proved that by using a multichannel protocol, the number of packet losses and retransmissions can be reduced. This is because of the efficient use of the wide spectrum where MCRP chooses the channels with lower interference levels which indirectly helps to reduce the energy consumption of the nodes compared to the other cases in single-channel protocol.

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