An Energy Efficient Cross-Layer Network Operation Model for IEEE 802.15.4-Based Mobile Wireless Sensor Networks

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***Abstract*— IEEE 802.15.4 mobile wireless sensor networks (MWSNs) have been investigated in literature. One major finding is that these networks suffer from control packet overhead and delivery ratio degradation. This increases the network's energy consumption. This paper introduces a cross-layer operation model that can improve the energy consumption and system throughput of IEEE 802.15.4 MWSNs. The proposed model integrates four layers in the network operation: 1) application (node location); 2) network (routing); 3) medium access control (MAC); and 4) physical layers. The location of the mobile nodes is embedded in the routing operation after the route discovery process. The location information is then utilized by the MAC layer transmission power control to adjust the transmission range of the node. This is used to minimize the power utilized by the network interface to reduce the energy consumption of the node(s). The model employs a mechanism to minimize the neighbor discovery broadcasts to the active routes only. Reducing control packet broadcasts between the nodes reduces the network's consumed energy. It also decreases the occupation period of the wireless channel. The model operation leads the network to consume less energy while maintaining the network packet delivery ratio. To the best of our knowledge, the presented operational model with its simplicity has never been introduced. Through simulation-based evaluations, the proposed model outperforms the conventional operation of IEEE 802.15.4-based network and the energy efficient and QoS aware multipath routing protocol in terms of energy consumption by roughly 10%, twice less control packet overhead, on-par end-to-end delays and comparative packet delivery ratios.**

***Index Terms*— Cross layer design, energy efficiency, mobile nodes, wireless sensor networks, sensor system networks.**

I. Introduction

MOBILITY in wireless sensor networks (WSNs), can have a profound effect on the network operation [1]. This effect is diverse according to several parameters that include: application diversity, network topography (topology), network connectivity and deployed node(s) or sensed event(s) location estimation. Sensor node mobility can be divided into two categories: limited mobility where there are specific nodes that roam around the network to perform an exclusive task (e.g., mobile sink nodes) and random mobility where the nodes (sensor nodes) roam around the area of deployment to collect the data needed for the application [2]. Mobility as a problem has either advantageous effects or disadvantageous ones.

Advantages of introducing mobility to the network can be listed as below [3]:

1. Applications: introducing mobility to the network can enlarge the scope of applications to implement WSNs. Applications such as: social activity monitoring, cattle monitoring, swarm bot actuated networks and more [1].
2. Topography and network connectivity: since WSNs transfer their data in a multi-hop fashion, mobility can enhance the network operation by changing the location of the nodes leading to create different links to the destination required.
3. If mobility is limited to special nodes, e.g., sink node(s), the stationary nodes then can be relieved in terms of links generated to the destination node. The sink node(s) can roam around through stationary nodes and gather the information sensed by sensor nodes. Mobile sink nodes can also enhance the network connectivity by minimizing the congestion that can happen during network traffic flow [4].

Mobility can introduce a critical challenge to the operation of the deployed network:

1. If mobility is limited to special node(s), then those nodes can suffer from a bottleneck problem. A considerable plan and calculations are required to estimate the optimum number and paths for the special node(s) to cover the deployed network [5], [6].
2. If mobility is random. i.e., sensor nodes are also mobile in the network, the effect is greater as the network topology changes become rapid and that affects the connectivity of the nodes. Topology changes have an effect on the routing operation as the links need to be rebuilt frequently; therefore, there is an increase energy consumption of the nodes. Mobility affects the MAC protocol operation because the connectivity can suffer from broken connections due to the transmission range of the wireless interface. The location of the sensor node(s) in random mobility is of importance because the sensed event is attached to the location of the sensor node. In a mobile scenario, a localization mechanism

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becomes a frequent operation leading to an increment in node(s) energy consumption [7].

As aforementioned, mobility is a serious issue if introduced in WSNs operations. It has its advantages and disadvantages on diverse levels of the network operation. The focus of this paper is the random mobility of the deployed sensor nodes and how it has effects on the networks operation in terms of the connectivity and location estimation of the nodes. The connectivity issue is dealt with by using routing protocols and MAC protocols as both layers are responsible of insuring an available connection between one hop and another. The location information is an application layer attachment; however, it requires a specific mechanism to estimate the location of the mobile node(s).

II. Related Work

Reference [8], introduced a cross-layer operation mechanism that considers the routing, MAC and physical layers to maximize the network life-time. The model assumes the network problem as convex where $G(P, h(n_i))$ is the network graph and P is the set of nodes deployed and $h(n_i)$ is the amount of data from node i that is needed to represent the sensed event in the deployment area. The nodes deployed are static. The model has not been tested for WSNs with mobility characteristics.

The XLP protocol is a cross-layer protocol that employs the concept of initiative determination. Introduced by [9], the protocol represents one of the first models to introduce a tight coupled cross-layer operation into one module.

A service oriented cross-layer operational model has been introduced by [10]. The protocol aims to prolong the network life-time by maintaining the number of nodes required to achieve the application requirement. The application-based operation tracks the duty-cycles of nodes so that the network is maintained for the sensed services which are available.

SAMAC [11], is a cross-layer model that combines the slotted operation of the MAC protocol with the direction of the attached sectored direction antennas. The communication interferences between the nodes are lowered because the communication is between the directional antennas as omni-based antennas can infer higher interference. The zones of connections are directionally related to the directional antennas. The MAC mechanism starts by using a CSMA/CA operation to converge the network and when the network is fully converged, the nodes then start transmission using a TDMA operation.

Reference [12] proposed Breath, a cross-layer model for industrial applications. The protocol investigates the coupling of randomized routing, medium access control and nodes duty-cycle to achieve a longer life-time. Breath adapts to traffic variation and channel conditions. The environment of deployment is industrial facilities where the nodes are stationary and are deployed in a planned setting.

Transmission power control is introduced in cross-layer operation as in [13]. The proposed operation utilizes a TDMA-based MAC mechanism with a clustering routing algorithm. The transmission power control is achieved based on the path-loss characteristic of one hop between connected nodes. If the nodes are mobile, the transmission recalibration operation of the whole network has to be performed in a frequent manner. Since the approach assumes that the transmission power control is performed for every packet type, the recalibration process becomes energy expensive.

A cross-layer operation model has also been investigated to improve the operation of one layer, such as [14]. The method proposes a solution for the hidden terminal problem that the IEEE 802.15.4 MAC protocol suffers from. The solution investigates the overhearing of the hidden nodes and based on their overlapping signals in the physical layer, the protocol addresses the hidden nodes.

A cross-layer geographic-based (location-based) routing with mobile sink nodes has been proposed by [15]. The protocol utilizes the mobile sink nodes' location broadcasting to the neighboring nodes. The location information is then reached by the sink using those neighbor nodes overhearing of the location to deviate the data transmission accordingly.

Reference [16] proposed a ZigBee-based mobility enhanced topology configuration approach for MWSNs. The model utilizes the nodes' locations and their probabilistic behavior to be near the routing path. The final model improves the delivery ratio of the network by forcing the nodes to gather near the network tree root. The scope of this paper is cross-layer operational enhancements for MWSNs.

Routing focused on cross-layer mechanisms has been introduced for MWSNs [4]. A mobility-based clustering routing protocol (MBC) for wireless sensor networks has been proposed by [17]. The protocol incorporates the node mobility direction and cluster head residual energy to create a metric for time slotting the connection between the nodes using the TDMA mechanism. The protocol utilizes the transmission power control between cluster head and non-cluster head nodes. The cluster heads are assumed to be stationary and some of the deployed nodes are mobile.

Location enhanced routing has also been introduced by [18] for MWSNs. The location aware and fault tolerant clustering routing protocol [18] is an example of such approaches. The protocol improves the clustering mechanism by assuming that the cluster heads are chosen if there mobility indicator is the lowest and there residual energy is above the threshold value. However, the mechanism also assumes that the cluster heads, when chosen, are to be stationary or remain in the same cluster the whole operational period. This limits the network's general operational flexibility.

An Energy Efficient and QoS aware multipath routing protocol (EQSR) has been proposed by [19] for WSNs. The protocol utilizes multipath routes to find the best path from source to destination. The protocol cross -layers its routing path choice criteria based the physical layer elements of the next hop. Those elements are the node(s) residual energy, interface buffer availability and the connection signal-to-noise ratio (SNR) between two neighbor nodes. The protocol is an example of the tight cross-layer of information between the physical-layer and the network layer (routing protocol).

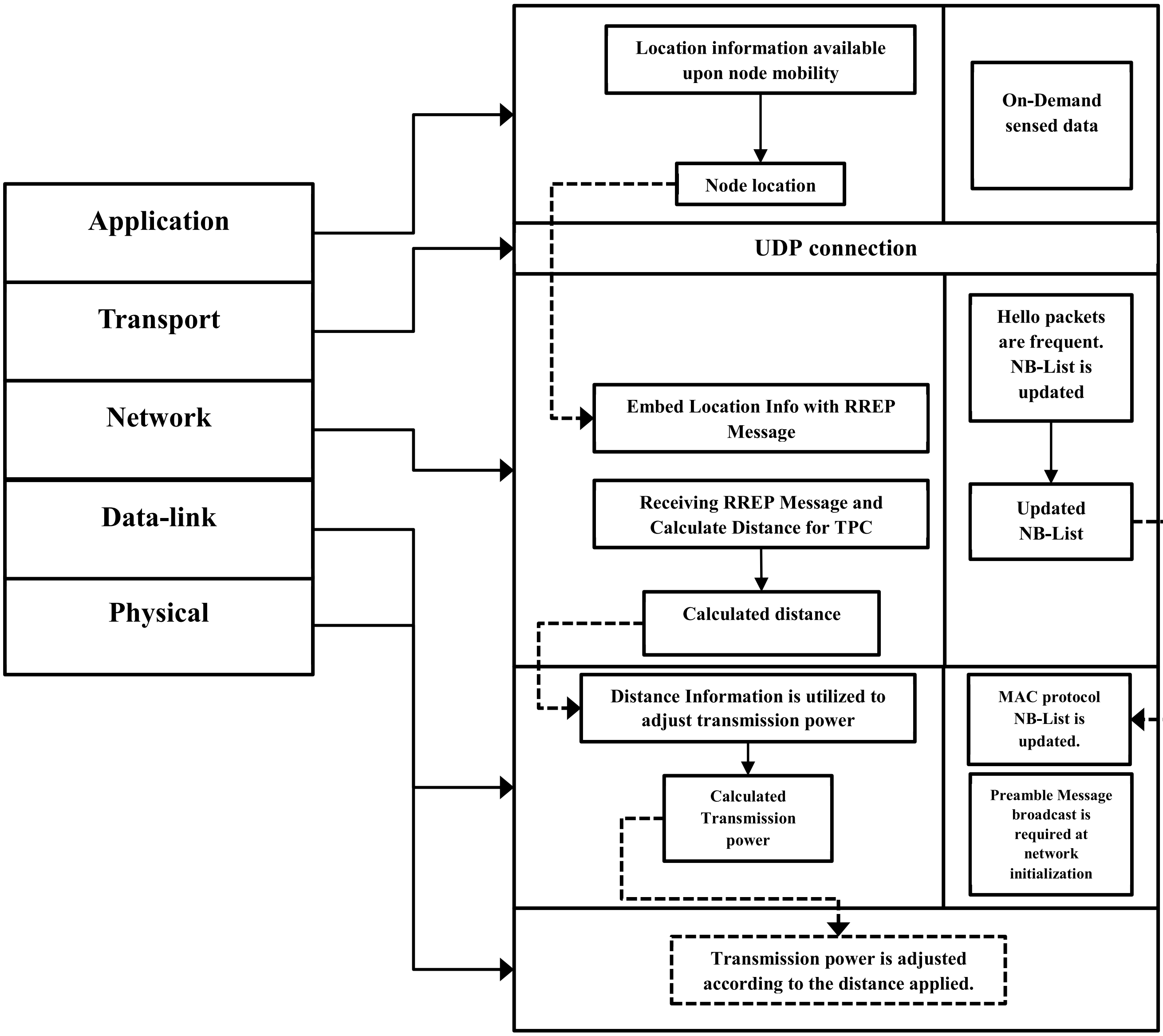

Fig. 1. Operational model detailed process diagram.

The proposed cross-layer assumes no clustering mechanism has been implemented. This makes the network more flexible in terms of new nodes joining the network.

III. Proposed Model

The abstract illustration of the cross-layer operational model is detailed in Fig. 1. To show the activity of each layer, an abstract TCP/IP model was placed beside the operational model.

At network initialization, the mobile node started to broadcast a neighbor discovery message to initiate neighbor(s) information collection and store it in a neighbors' list (NB-List). After the initialization process, if a node in the network had data of interest to send, attached with this data was the location information of the mobile node. The location information in the node is provided by either a GPS module attached to the node or any other methods where the nodes are able to estimate their individual locations. This node then started sending route request (RREQ) packets to establish a route to the destination node. The routing protocol utilized in the operation model utilizes a periodic neighbor maintenance message which is a hello packet. Hello packets are broadcast packets; therefore, it was possible to utilize the neighbor list from the network layer in the data-link layer. This eliminated the need for neighbor discovery messages to be sent by the MAC protocol. After the destination node received the RREQ packets, it replied by sending a unicast route reply (RREP) packet. The destination node embedded its own location information in the RREP message and sent it back to the next hop node in the reverse route. Fig. 2 illustrates the RREP packet structure after embedding the location information. The next hop node in the reverse route calculated the distance between it and the destination node and exported this information to the data-link layer. The MAC protocol utilized the transmission power control-based

Type	|R|A|	Reserved	Prefix	Hop Count
Destination IP Address				
Destination Sequence Number				
Originator (Source) IP Address				
Lifetime				
Location information				

32 bits

Fig. 2. RREP Message structure after embedding the location information. A 32-bit field is required for the location information as it is relevant to the implemented simulations. 16 bits for the X-axis and 16 bits for the Y-axis. It is possible to store the location information (Latitude and longitude) in a 32 bit integer number by using Virtual Earth's tiling system method [20].

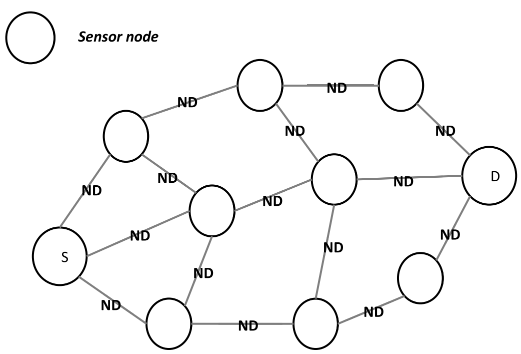

Fig. 3. Network activity state at time stamp t_s.

on the distance information and calculated the required power to use when sending data packets back to the destination node. The transmission power and range is calculated by implementing the radio propagation model according to the distance calculated by the nodes. The distance between two nodes is calculated as the Euclidian distance between two points. To minimize the broadcast of the control packets, the nodes that were only in the active route(s) were allowed to periodically broadcast hello packets to their neighbors. Active route is the route that has been established to transmit data from source node to destination node after the route discovery operation.

This operation was repeated through all nodes until the source node. After the established route passed its lifetime and there was no data of interest to send, the nodes engaged in the operation went into sleep state. Nodes which were still involved in another route were active as the operation required.

A. Energy Model of the Cross-Layer Operation

The network energy consumption model can be described as follows: Let Fig. 3. represent the example network at time stamp t_s. The utilized network model is described as an undirected connectivity graph $G\,(V, E)$, where V is a finite set of nodes, and $(i, j) \in E$ represents a wireless link between node i and node j. The mobile node'(s') speed, position, moving direction and transmission range can be represented as a function to indicate a sensor node's condition in the network in a Cartesian coordinate, that is:

$$\Phi i(t) = f((x(i,t), y(i,t)), \upsilon(i,t), \theta(i,t), Ri) \tag{1}$$

where f represents the node's state at time, $(x(i,t), y(i,t))$ is the position, $\upsilon(i,t)$ is the speed, $\theta(i,t)$ is the moving direction of node i at time t and Ri is the communication range of node i. If node j is a neighbour of node i, the relative function can be expressed as:

$$\Phi_{j-i}\,(t) = g((x(j\_i,t), y(j\_i,t)), \upsilon(j\_i,t), \theta(j\_i,t), Ri, Rj) \tag{2}$$

where g represents the neighboring nodes i and j states, $(x(j\_i,t),\ y(j\_i,t))$ is the relative position, $\upsilon(j\_i,t)$ is the relative speed, $\theta(j\_i,t)$ is the relative moving direction of node j to node i at time t and Ri, Rj are the communication range of node $i,\ \ j$, respectively.

At network initialization (or when a node has data of interest), the nodes start to broadcast ND packets to establish their neighbor tables where the neighbor nodes $\{N_R\} \in \{N\}$. Therefore, the energy consumed by the network is the energy consumed by each node after sending and receiving ND packets (3).

$$P_{initialization} = \sum\nolimits_{i \in N_R} P_{ND}(\Phi i\ (t_s + t_{ND})) \tag{3}$$

where P_{ND} represents the power consumed by one for sending one ND packet, t_s represents the time stamp of network initialization and t_{ND} represents the time required to transmit and receive ND packets by each node. The second step is to search for a route to the destination node by broadcasting hello packets to keep the RREQ messages between the nodes. The power consumed by the nodes at this state is the power consumed for sending hello packets plus the power consumed by broadcasting RREQ messages as described in (4):

$$P_{route1} = \sum\nolimits_{i \in N_R} P_{RREQ}\left(\Phi i\left(t_{RREQ}\right)\right) + \sum\nolimits_{i \in N_R} P_{Hello}\,(\Phi i\ (t_H)). \tag{4}$$

Where P_{RREQ} represents the power consumed by the nodes for broadcasting and receiving RREQ packets, t_H represents the time required to transmit a hello packet and P_{Hello} is the power required for the periodic transmission of hello packets. The destination node then starts sending back RREP messages. RREP messages include the information of the node's location that has sent the RREP message. This will create a different set of nodes $\{K\}$ where $(K \in N)$ as the RREP message is a unicast message. A node is included in set $\{K\}$ if the node receives a RREP packet. The proposed operation limits the periodic broadcast of hello packets to the nodes only involved in the active route. Therefore, the energy consumption at this state is represented by (5):

$$P_{route2} = \sum\nolimits_{i \in K} P_{RREP}(\Phi i\ (t_{RREP})) + \sum\nolimits_{i \in K} P_{Hello}(\Phi i\ (t_H)) \tag{5}$$

Where P_{RREP} represents the energy consumed by the node to transmit and receive RREP packets. The hello packets

are only broadcast between the nodes if $i \in \{K\}$. The final step is represented by sending data packets from the source node. Because the source node and the nodes in the middle of the route know the distance from them to the next hop in the route, these nodes will adjust their transmission power to the required distance. This makes the power consumed during the data transmission state a function of both distance and time consumed for transmitting full data packet(s). Equation (6) represents the power consumed at data transmission state.

$$P_{DATA-State} = \sum\nolimits_{i\in K} P_{DATA}(\Phi i\ (t_{DATA}, R_{Distance})) + \sum\nolimits_{i\in K} P_{Hello}(\Phi i\ (t_H)) \quad (6)$$

where P_{DATA} represents the power consumed by the transmission of data packets between the nodes, t_{DATA} represents the time required to send data packet(s) and $R_{distance}$ represents the distance between node i and node j (i is the sender node and j is the receiver node). The hello packets' broadcasting power consumption is bounded by the lifetime of the route established. Therefore:

$$\sum\nolimits_{i\in K} P_{Hello}\,(t_H)\ \exists\ if\ \ (i \in \{K\})\,\&\,\left(Route_{lifetime} > 0\right) \quad (7)$$

If $\left(Route_{lifetime} = 0\right)$, and there is no data of interest to send to the destination node, the nodes can go back to dormant mode (sleep mode). The route life time is defined in the attributes of the routing protocol. The final network power consumption model can be represented by (8):

$$P_{Network} = P_{initialization} + P_{route1} + P_{route2} + P_{DATA-State}. \quad (8)$$

This operation minimizes the energy consumption at several levels:

The neighbor discovery packets are needed only at the initialization process of the network to build the neighbor tables. After initializing the network, neighbor discovery packets are not needed to be broadcast anymore because the hello packets periodic broadcasting will maintain the neighboring nodes for the active route.

Knowing the location of the next hop to adjust the transmission power will minimize the power consumed if the distance between the nodes in range is short. The transmission protocol mechanism sets the transmission power for the node as long as the transmission power (TP) required does not exceed the transmission range ($TP_{Adj.} \leq TP_{MaxRange}$).

Periodic hello packet broadcasting becomes limited to only the nodes involved in the established route. Periodic hello packets are also limited to the life time of the route established.

The proposed mechanism is unique as it cross-layered the operation of three layers: application, network and MAC layers to achieve the improvements in terms of the energy consumption of the network in general. The transmission power control mechanism is activated only at the data transmission state to avoid unreliable connectivity between the nodes at other network states (convergence, route establishment ... etc.).

B. Model Evaluation Metrics

The operation model was evaluated by the following metrics:

Energy per packet: The energy per packet metric represented the operational model's energy efficiency during network operation. Energy per packet was calculated as the energy consumed per network to the number of successful packets transmitted. The energy per packet was calculated for the operational model as well as the methodologies compared to under the same hardware/physical layer specification.

$$E_{Packet} = \frac{E_{Network}}{Number\ of\ Packets\ transmitted} \quad (9)$$

System Throughput: The throughput metric represented the system data productivity during the network operation. System throughput was represented by the amount of data that was delivered from a source to a destination during a period of time.

$$Throughput = \frac{Number\ of\ packets\ received}{Network\ operation\ time} \quad (10)$$

Packet delivery ratio (PDR): PDR represented the percentage of the successfully transmitted packets to the number of generated packets.

$$PDR(\%) = \frac{Number\ of\ received\ packets}{Numberof\ generated\ packets} \quad (11)$$

End-to-End Delay: The End-to-End delay metric was defined as the average time consumed to transfer one packet in the network. The End-to-end delay was calculated as the summation of the delays of every successful packet sent and divided by the total number of packets transmitted.

$$E - E_{Delay} = \frac{\sum_{i=0}^{n} E - E_{delay_i}}{n} \quad (12)$$

Where $E - E_{Delay}$ is the end-to-end delay for n packets, n is the number of packets received and i represents the packet id.

Normalized routing load: The normalized routing load was calculated as the number of control packets sent and forwarded to the number of successfully received data packets by the destination node.

$$Normalized\ routing\ load = \frac{Number\ of\ control\ packets\ sent}{Number\ of\ data\ packets\ delivered}. \quad (13)$$

C. Model Evaluation Environment

The operational model target application was mobile node tracking for social purposes inspired by the application proposed in [1]. Mobile sensor nodes roamed around a fixed deployment area (Fig. 4). The application environment assumptions were as below:

1) The system was homogenous, i.e., the nodes had the same type of equipment and capabilities (Hardware and software).
2) All sensor nodes were mobile.
3) A stationary sink node was deployed in the network.
4) The deployment surface was flat.
5) A line-of-sight was present between the nodes in the transmission range vicinity of each other.

The propagation model utilized in the evaluation process was the Two-Ray Ground model as the nodes had a present

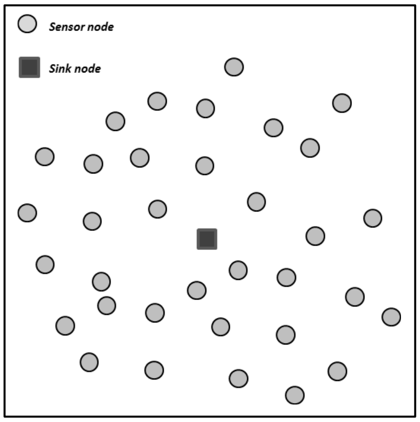

Fig. 4. Deployed network example.

line-of-sight and no obstacles in between. The Two-Ray Ground model had been used for evaluating mobile WSN operations in [4], [5], [16], [21], [22], and [23]. The energy model that the nodes followed contained the following states: transmission power, reception power, idle/listening power, sleep power and state transition power.

$$E_{node} = \sum E_{tx} + E_{rx} + E_{idle} + E_{sleep} + E_{trpower} \quad (14)$$

where E_{tx} represented the transmission energy of the node, E_{rx} the reception energy, E_{idle} the idle/listening energy, E_{sleep} the nodes' sleep energy and $E_{trpower}$ represented the state transition power.

IV. Results and Discussion

Extensive simulations have been performed to evaluate the Cross-layer approach. It has been evaluated using NS2 [24]. The proposed model has been compared against the EQSR protocol and the standard model of IEEE 802.15.4. The scenarios had a deployment area of 200 × 200 meters. The nodes deployed were all mobile with a stationary sink node placed in the middle of the simulation area. There were seven data sources randomly chosen for all of the scenarios. All of the sources transmitted their data to the sink node. The applications started consecutively for each source node with 10 seconds difference between each source application start time. The mobile nodes had random mobility directions. The transmission power and reception power considered mimicked an IEEE 802.15.4 cc2420 model [23], [25]. The mobile nodes have randomly timed mobility pauses. The period of each pause was 50 seconds. The transport protocol used was UDP. The simulation period was 500 seconds. The minimum node mobility speed was 1 m/s and the maximum was 3 m/s. The proposed cross-layer model was compared against a model proposed by [26] for WSNs. Table I illustrates the parameters for the simulations. The transmission range and the carrier sense range were the same 40 meters. This means that if a node left another node's(s') transmission range there was no possible overhearing from the nodes beyond the transmission range. The queue length is 150 following the simulation model proposed in [23].

Each simulation scenario had been run for 31 times and a 95 confidence interval has been taken for all the results.

TABLE I
Simulation Parameters

Simulation parameters	Values
Number of nodes	15,20,25,30,35, 50, 75, 100
Initial energy (Joules)	1000
Mobility	1 m/s - 3 m/s
Propagation model	Two Ray Ground
Transmission range	40 meters
Simulation time	500 seconds
Mobility pause period	50 seconds
Routing protocol	AODV
MAC protocol	IEEE 802.15.4
Number of sources	7 nodes
Transport protocol	UDP
Application	CBR
Packet size	100 bytes
Queue length	150 packets

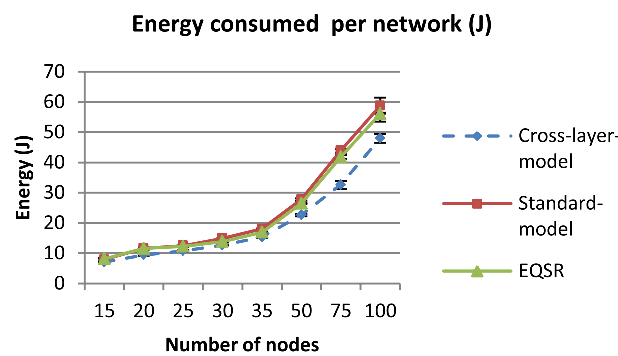

Fig. 5. Total network energy consumption.

A. Energy Consumption Results

The energy consumption of the network and the energy consumption per packet results are shown in Fig. 5 and Fig. 6. The results show an improved performance of the network energy consumption. The proposed operational model consumed energy lower than the standard IEEE 802.15.4 model. The energy consumption per packet was also lower for the cross-layer model than the standard model. The low energy consumed per packet was because the packet delivery ratio for the cross-layer model was higher than the standard model and the network energy consumption was lower.

The network energy consumption was lower because the cross-layer employs both transmission power control and control packet minimization. The transmission power control mechanism had its lowest effect at the lowest number of deployed nodes as the distances between the nodes were higher. When the number of deployed nodes increased, the energy consumption gap increased. This means that the transmission power control was taking its effect as the distances between the nodes became shorter.

The control packet minimization procedure improved the network energy consumption because the number of

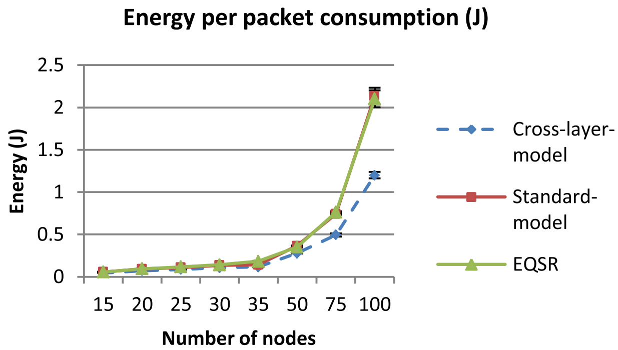

Fig. 6. Energy consumption per packet.

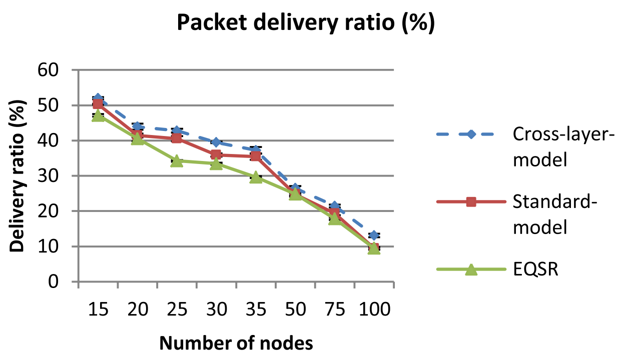

Fig. 7. Packet delivery ratio.

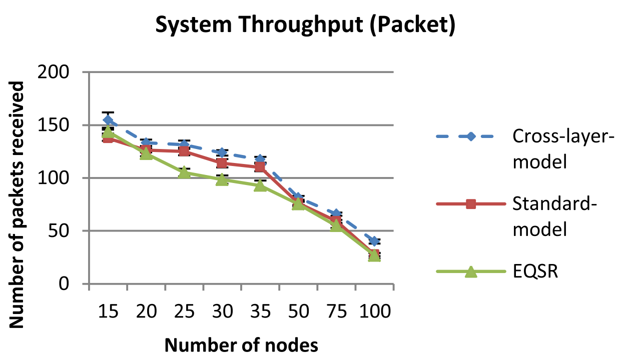

Fig. 8. Network total throughput.

control packets had been lowered (the results are illustrated in section IV.D). While EQSR utilizes the physical layer to choose the best route, the mechanism improved the network energy consumption slightly more than the standard model.

B. Network Throughput Results and Analysis

The throughput and packet delivery ratio results are illustrated in Fig. 7 and Fig. 8. The cross-layer operational model improved the packet delivery ratio (PDR) of the standard model by almost 2%. The trend of the throughput was the same as in the PDR results. The cross-layer model minimized control packet overhead which resulted in less channel occupation during packet transmission. While the packet delivery and throughput have been improved, The overall trend was degrading as has been reported in [2] and [27]. This was mainly because the IEEE 802.15.4 MAC protocol suffered from delivery degradation when the number of the deployed nodes increased. The MAC protocol also showed unreliable

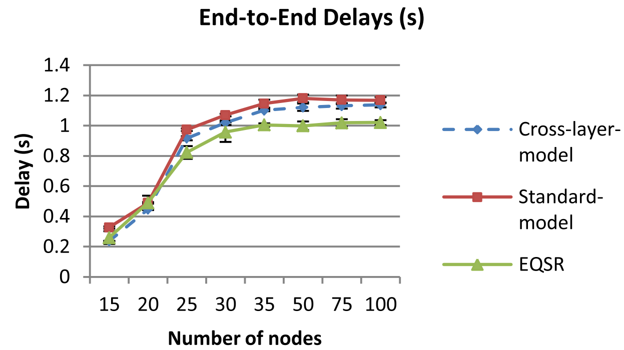

Fig. 9. Average end-to-end delays for the network.

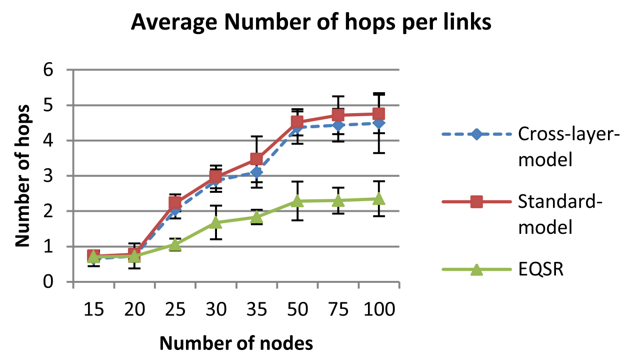

Fig. 10. Average number of hops for the created links in the network. The higher the number of hops, the longer the path was to the destination; therefore, the end-to-end delays increased.

operation when nodes in the network were mobile. There have been several approaches to overcome the issue of the unreliable operation of the IEEE 802.15.4 protocol; however; it was not in the scope of this paper. The EQSR protocol produced the lowest system throughput which resulted in lower packet delivery ratios.

C. Delays Results

The cross-layer model improved, marginally, the end-to-end delays as illustrated in Fig. 9. The channel occupation was an effective parameter on the hop-to-hop message propagation delay. The mobile nodes were required to check for the medium if it was available or not. Controlling the number of broadcast control packets deployed in the network controlled the wireless channel occupation and lowered the link(s) congestion. Minimizing the channel occupation improved the overall end-to-end delays. The multi-path mechanism of EQSR improved the average end-to-end delays. EQSR utilized the network interface buffer size as one of the metrics of choosing the next hop in the active route.

The results in Fig. 9 show a trend where the end-to-end delays rose by a noticeable margin when increasing the number of deployed nodes from 20 to 25 nodes. The margin then started to level for 30 and 35 nodes. The increase in the number of deployed nodes increased the number of the neighbor nodes to the sink. Therefore, the number of data forwarding sources to the sink. This led to a delay at the sink node to accept the reception of the data from the nodes resulting in the increase in end-to-end delays.

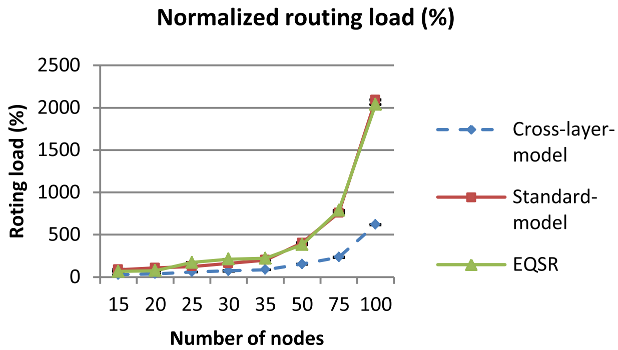

Fig. 11. Normalized routing load.

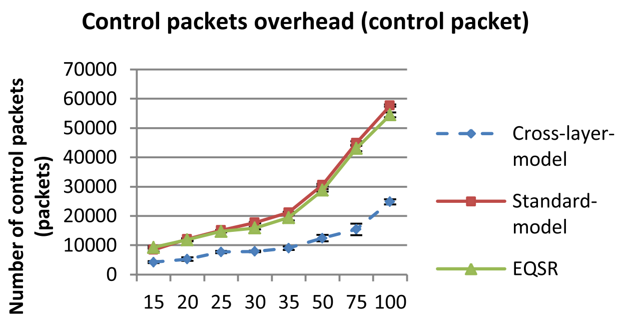

Fig. 12. Control packets overhead.

End-to-end delays increased also because the routes created had a higher number of hops to the destination (Fig. 10). EQSR had a lower number of created hops per link than the standard model and the cross-layer model; therefore, it had fewer over all end-to-end delays.

D. Control Packets Overhead Results

The cross-layer model implemented a mechanism to decrease the control packet overhead of the network. Fig. 11 and Fig. 12 show the results. The control packet overhead has been immensely decreased. The order of the improvement was about two times less than the standard model. That was a lot of control packets being transmitted periodically without practical use. The cross-layer model improved the number of control packets by limiting them after network convergence to the nodes that were involved in active routes.

The other nodes went to the dormant state if they had no data for transmission. The EQSR protocol had a higher normalized routing load since it produced lower packet transmitted. As for the number of control packets, it was generating a lower number of packets than the standard model. However, the number of generated control packets by the EQSR was higher than the cross-layer model since the protocol did not employ any control packet minimization or control.

V. Conclusions and Future Directions

This paper has proposed a simple, intuitive yet highly effective cross-layer network operational model for MWSNs. The network model employs two major mechanisms: the first is controlling the amount of control packets being broadcast in the network to provide a relief for the communication channel between the nodes. The control packet minimization process focuses on the broadcast packets, mainly neighbor, discovery mechanism at the MAC layer and the neighbor discovery packets (hello packets) at the routing layer. The second mechanism is transmission power control that is dependent on the node'(s') location. The transmission power control mechanism is only active when the route is established; therefore, its effect is guaranteed at the data transmission state. Combined together results in energy efficiency, higher throughput and lower end-to-end delays than the standard model. To our knowledge, such a combination in the cross-layer operation with four layer cooperation has not been introduced before and is unique.

Future directions for the proposed model is to minimize more control packets especially RREQ packets as they are also broadcast packets. A possible mechanism is to program the mobile so that they know where the sink node is.

Therefore, by implementing a directional broadcast flooding, this should minimize the number of control packets being broadcast and improve the channel quality. Another possible improvement over the proposed model is to have heuristic calculated information about the active route life-time. By merging the information of the mobile node(s) movement direction and speed, the active route can be programmed to have a life-time equal to when the first node of this active might leave the connectivity range. Such mechanism can minimize the link error handling messages between the nodes.

Applications that can benefit from such implementation can be related to elder care centers or social activity monitoring, e.g., kindergarten monitoring related applications.

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