An energy efficient algorithm for image transformation in Wireless Sensor Networks

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Abstract— **In recent years Wireless Sensor Networks (WSN) have experienced an exponential growth. Among the several applications for WSN, image processing and its delivery is one of the most challenging due to the limited resources that sensor nodes offer. In this paper a protocol based on distributed Discrete Wavelet Transform for wireless communication is presented. The goal is to distribute the workload among several sensor nodes to have maximum lifetime of the network. Simulations are done with Cooja, the Contiki simulator; programs are written for TinyOS.**

Keywords- Wireless sensor networks, Discrete Wavelet Transform, Distributed Transform, lifetime of the network;

I. INTRODUCTION

Wireless Sensor Networks consist of spatially distributed autonomous devices (nodes) that are able to communicate with each other. Thanks to the use of on-board sensors, these devices can monitor the surrounding environment and exchange this information with other nodes in the network. The main features of these nodes are their compact size, low computational speed, limited on-board memory, and being battery-powered. One of the possible applications for these sensor nodes is image acquisition and transmission, not a well-suited task given the limited resources of these devices. Images, in fact, require a considerable amount of memory for them to be stored and high bandwidth to be transmitted. Since the transmission of data via radio is very energy consuming, a reduction of the data to be transmitted, and consequently image compression is advisable.[1]

In recent years the Discrete Wavelet Transform (DWT) has gained widespread approval for image compression.[2]

The Discrete Wavelet Transform is a two-dimensional separable filtering applied across rows and columns of the input image. Since it is based on the concept of multi-resolution, it is particularly suitable for image compression with multiple levels of quality. Another positive aspect of the DWT is that most of its data output is highly redundant, therefore, compression algorithms give excellent results.[3],[4]

The DWT is achieved by applying a low-pass filter (L) and a high-pass filter (H) to the input image row by row and then filtering the output column by column using the same filters. The output consists of four sub-bands: LL1 is the approximation sub-band, HL1 is the horizontal detail sub-band, LH1 is the vertical detail sub-band and finally HH1 is the diagonal detail sub-band (Fig. 1).

The process can be repeated on the LL1 sub-band obtaining a 2-level DWT whose sub-bands are named LL2, HL2, LH2, HH2.

Performing the DWT or any other compression algorithm requires high computational power and memory, features which, most of the wireless sensor networks are lacking. It becomes necessary then that the workload is shared among the sensor nodes so to perform a Distributed Wavelet Transform. [5],[6]

In this paper we consider a mechanism to process the Distributed DWT in an energy-efficient way in order to maximize the network lifetime. [7],[8] It is then considered a way to deliver the processed image from a source to a destination simultaneously maximizing the image quality, while minimizing the energy waste to ensure the maximum network lifetime. [9]

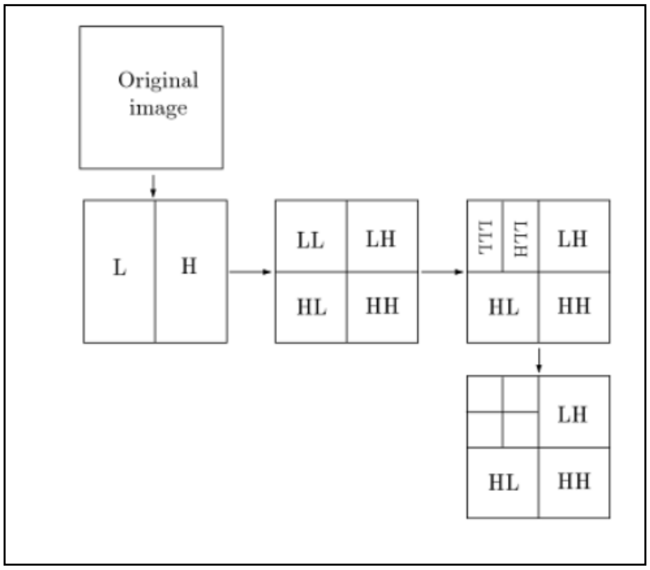

Fig. 1. Wavelet spectral decomposizion.

II. BASIC IDEA

To explain our idea, we start with a network topology that is shown in Fig. 2: Communication link is available between the Base Station (BS) and the first tier nodes, between the first tier nodes and the second tier nodes and also between the second tier nodes and the sink.

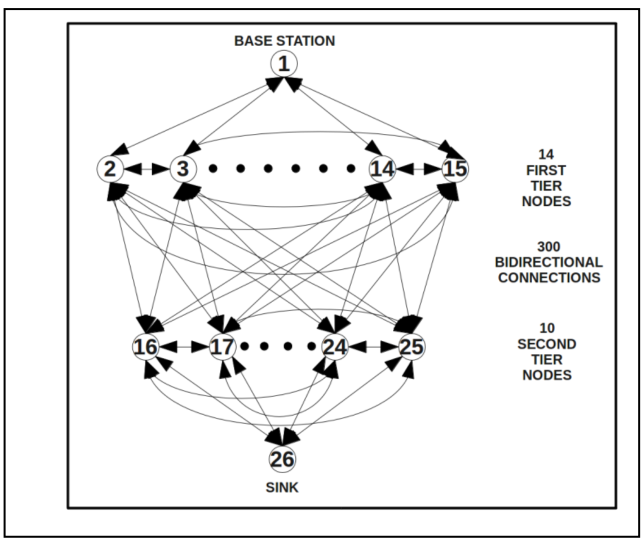

Fig. 2. Proposed network topology.

In the simplest case, let suggest transmitting a grayscale image within the shown network. Because of performing the Distributed DWT, four nodes in each tier were selected randomly. The Base Station holding the image to be processed splits the image in 4 tiles, randomly selects four nodes of the first tier (one of which is elected as Master Node) and sends each one of them one of the tiles. Each node performs a 1 level DWT on their received image chunk, computing the approximation and detail coefficients (LL1, HL1, LH1, HH1) then sends the processed data to the elected Master Node (MN). The Master Node combines the received image chunks, randomly selects four second tier nodes, one of which elected as Master Node, then sends each one of them a portion of the LL1 sub-band on which they will perform a 1 level DWT. The processed data is then sent to the second tier master node which combines the received data thus obtaining a two-level DWT. The processed image is then sent to the Sink (such as node #26 in Fig. 2).

The random selection of nodes does not ensure that the workload is equally partitioned amongst the different nodes of the network, especially if the nodes are used for several tasks, a common scenario in WSN. For this reason the creation of a protocol for the exchanging of battery information has been considered.

Instead of randomly choosing the nodes, the Base Station requests battery information to the nodes of the network and selects the most suitable ones (i.e.: those with higher residual energy). Prior to sending the image to be processed, the Base Station broadcasts a Battery Status Request Message, requesting the nodes in the network to reply with their battery status. The structure of the packet is shown in Fig. 3. The packet is composed of a field named Flag; this field is set to 0 when the Base Station or a Master Node are requesting the battery status to other nodes, the field is set to 1 instead, when the nodes are replying to the battery request. The field Battery Level is composed of 8 bits and allows information about the percentage of remaining battery storage, giving an approximation of about 0.4%. This field is used in replies of battery status but it can also be used during battery request to specify the minimum value of battery charge that motes must have in order to reply to the Battery Status Request Message and eventually take place in the DWT process.

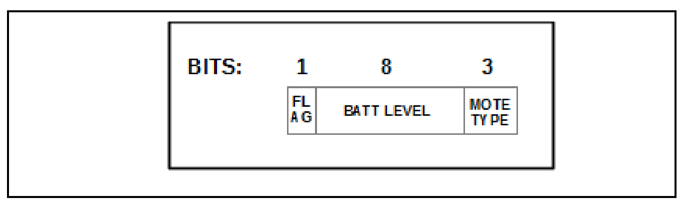

Fig. 3. Battery Status Message.

The last field of the Battery status Message is called Mote Type; this field is used to specify up to 8 different types of motes: as a matter of fact in typical WSN scenarios not all the motes in the network are the same. For example some might have more sensors on board than other, some might be more powerful than others in performing certain operations, etc.. With the use of this field the Base Station could select the type of sensor it is interested in and receive an answer about the battery status only by that type of sensors reducing the total radio traffic. The Base Station might as well request a battery status information for all the nodes of the network; in this case the Mote Type field is used by the nodes to specify what their type is; this info, together with the battery information, is used by the Base Station to determine which are the most suitable sensors for the job to be performed. The use of this protocol ensures that nodes with higher residual energy are used each time, this way extending network life. Since additional packets are being used compared to the scenario where nodes are randomly selected, the use of this protocol causes a slight increase in the consumed energy due to radio TX and RX of these packets. The results of a simple experiment for an 128×128 gray scale image can be seen in Fig. 4 and Table 1. In the example shown in the figures, the nodes selected to perform the DWT are nodes no. 2, 5, 10 and 14 (14 being the Master Node) for the first tier, and node no. 18, 21, 22, 25 (22 being the Master Node) for the second tier.

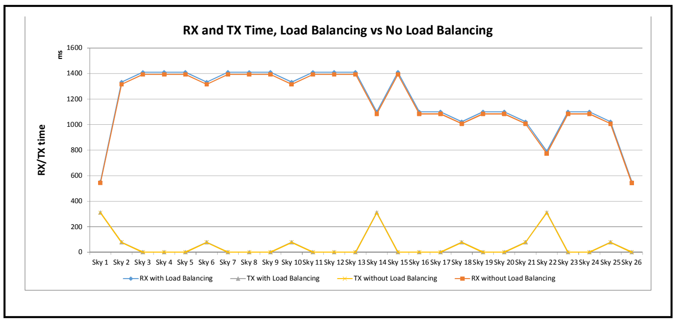

Fig. 4. RX & TX Time – Unbalanced vs Balanced.

The use of this load balancing protocol causes an increase of +1.30% of the total TX Energy used and an increase of 1.41% total RX Energy.

TABLE I. RX & TX TOTAL TIME – UNBALANCED AND BALANCED

Total Time [µs]	Type of Protocol		Energy Saving
	Load Balancing	*No Load Balancing*	
RX	30,775,064	30,345,718	1.41%
TX	1,411,606	1,393,427	1.30%

These results guarantee to continue generalization of the basic idea. This percentage of additional energy consumption is related to the case where the Battery Info Request/Reply packets are sent for each image to be processed. Since the processing of a single image does not considerably influence the battery status of the motes performing the DWT operations, these packets can be sent less frequently therefore reducing the influence of the balancing protocol on the total energy consumption: if, for instance, the battery status info is requested each 20 processed images, the additional radio energy consumption due to the balancing protocol drops down to about 0.07%.

Further reducing energy consumption could be done while sending the Battery Status Request Message information is sent only by busy nodes. Therefore, there are two case A and B:

CASE A refers to the scenario where the Base Station and the Master Node request battery status information for all the nodes of the network as seen in Fig. 3;

CASE B on the contrary refers to the scenario where the Battery Level and Sensor Type fields are set so that the battery status information is sent only by four nodes of the first tier and only four nodes of the second tier, which is the minimum number of nodes required to perform the two-level DWT.

The Base Station and the Master Nodes may specify a minimum battery level required and the type of node they're interested in receiving an answer from. A clever use of these parameters may significantly reduce the energy consumption caused by the load balancing protocol as shown in Fig. 5 and Table 2.

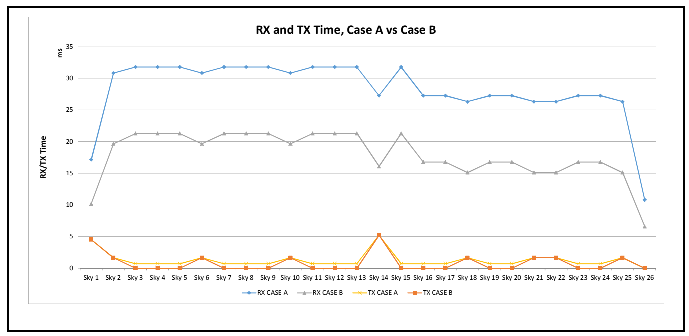

Fig. 5. Load Balancing Protocol – RX & TX time.

Simulation results show that with an appropriate use of the aforementioned fields it is possible to achieve up to 34% of TX and up to 36.57% of RX energy saving.

TABLE II. LOAD BALANCING PROTOCOL RX & TX TOTAL TIME

Total Time [µs]	CASE A	CASE B	Energy Saving
RX	734,366	465,806	36.57%
TX	32,479	21,288	34.00%

A. *Improved Method 1: Two-Level, Two-Stage DWT*

In the previous scenario, the image to be processed was split in four parts by the Base Station. This way, each sensor taking part in the DWT was performing all the necessary operations for a 1-level DWT. Another way to perform the distributed DWT is to share the several operations needed for the DWT among the sensors. It has therefore been simulated a scenario where, for each tier, four sensors are selected; in the first stage two of these sensors will perform the High-pass (H1) and Low-pass (L1) filtering on the image.

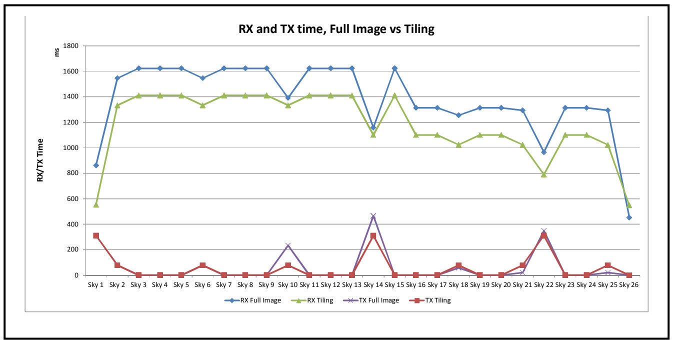

Fig. 6. Two-stage full image vs tiling RX & TX time comparison.

Once these operations have been carried out, the sensors will broadcast the processed data to the other three sensors which have been chosen to perform the DWT. This way each one of the four motes will have both the L1 and H1 components of the image, and will be able to perform the operations needed to obtain the LL1, HL1, LH1 and HH1 sub-bands. Finally, each sub-band is sent to the first tier master node which will forward them to the second tier nodes that will perform the 2nd-level DWT. In Fig. 6 and Table 3 the TX and RX radio traffic for computing the DWT using the two previously described techniques are compared.

TABLE III. TWO-STAGE FULL IMAGE VS TILING RX & TX TOTAL TIME

Total Time [µs]	Full Image	Tiling	Energy Saving
RX	35,884,108	30,775,064	14.24%
TX	1,624,482	1,411,606	13.10%

Since the two-stage technique involves the transmission of H1 and L1 as well, the simulation shows an increase of both the TX and RX data: the use of the tiling technique therefore ensures a saving of 14.24% Total RX Radio Energy and 13.10% of Total TX Radio Energy.

B. *Improved Method 2: Adding Synchronized Sleep*

A proper use of the Battery Level and Sensor Type fields allows a reduction of the used TX Energy as seen in the previous paragraph. The used RX energy remains still high though, due to the fact that each mote is continually listening to the radio channel, listening to packets that are not intended for the node itself. To reduce the RX power a modification to the balancing protocol has been made: after the Base Station or the Master Node receive battery status information from the nodes and choose the most suitable nodes to perform the DWT, they broadcast a Sync Message whose structure is seen in Fig. 7.

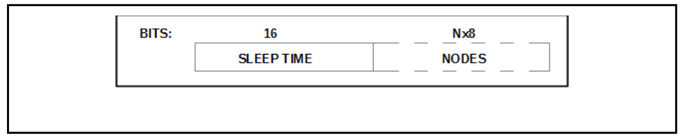

Fig. 7. Sync Message.

The packet is composed of two fields: Sleep Time specifies for how long the sensors will have to turn off the radio and enter sleep mode; time is expressed in milliseconds and goes from 0 to 65535 ms.

The field named Nodes instead contains the Node ID/Address of the motes that have been chosen to perform the DWT. When a node receives this Sync Message it checks the Nodes list; if its Node ID is not listed, it enters sleep mode for the amount of time specified in the Sleep Time field. Simulations have shown that at the price of +0.13% of TX energy due to the additional transmission of the Sync packet, a total of 66.58% RX energy is saved (see Fig. 8 and Table 4).

A disadvantage introduced by the use of the sleep mode is an increase of delay to compute the DWT: if the Base Station has an image ready to be processed but the sleep count down hasn't yet expired, the processing cannot begin. A proper selection of the sleep time according to the workload may minimize this delay and maximize the network life.

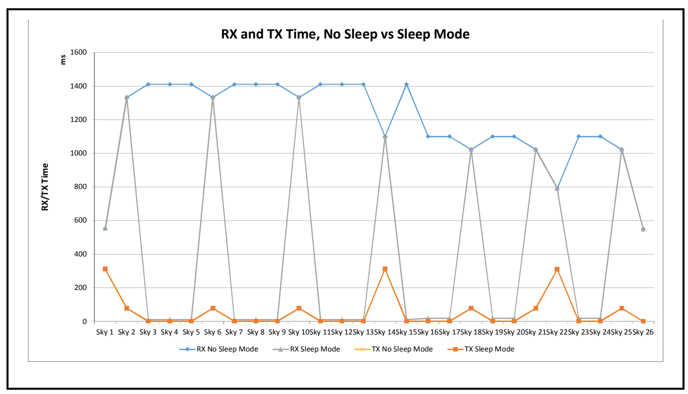

Fig. 8. Sleep vs No-sleep RX &TX time comparison.

TABLE IV. SLEEP AND NO-SLEEP RX & TX TOTAL TIME

Total Time [µs]	No Sleep Mode	Sleep Mode	Energy Saving
RX	30,775,064	10,286,322	66.58%
TX	1,411,606	1,413,412	-0.13%

III. Basic Idea In Image Delivery

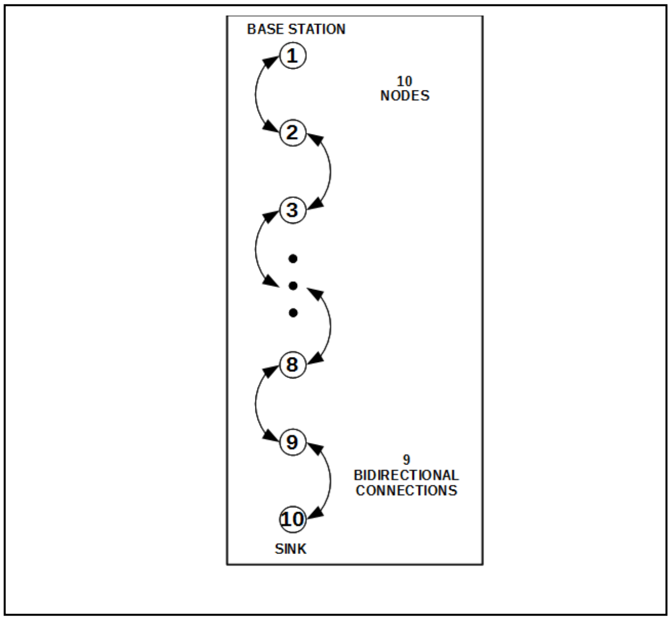

Fig. 9. Network Topology.

The proposed architecture concerned the processing of the image in a two tiered network; the following step is to deliver the processed image to destination. For this second task the network shown in Fig. 9 could be considered; node #1 holds the processed image that must be delivered to node #10. Each node communicates with other nodes within 1 hop distance. Since the image has been processed with a 2-level DWT, we can consider three different levels of quality available: the Low Quality level corresponds to the LL2 sub-band; the medium quality level is obtained by computing the IDWT with LL2 + (HL2, LH2, HH2) sub-bands. If all the sub-bands are received, it is possible to reconstruct the original image getting the highest quality image.

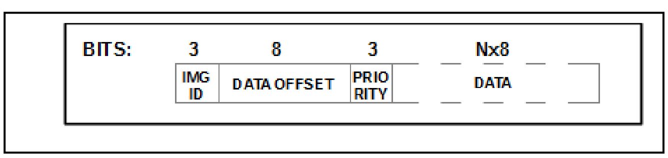

Fig. 10. Data packet structure.

Since forwarding data packets is very energy-consuming, sending each time all the sub-bands to get the maximum quality available may compromise network's life in a short period of time. To maximize network duration each sensor decides whether to send a certain sub-band depending on the status of its battery: if the mote's battery level is above a certain threshold it will forward all the sub-bands so that the maximum quality can be achieved at the receiver; if the battery level is between a certain interval it will forward only the sub-bands necessary to reconstruct the medium quality level image; on the contrary if the battery is low, it will forward only the LL2 sub-band packets. With this solution more images could be forwarded to destination although their quality won't always be optimum. In order to achieve this goal each packet is given a certain level of priority: LL2 is assigned the highest priority; the 2nd level detail sub-bands are assigned medium priority, while 1st level detail sub-bands are assigned the lowest priority. The packet structure is seen in Fig. 10.

Fields Img ID and Data Offset specify which image and fragment of image the data contained in the Data field refers to. The Priority field specifies which priority level the packet belongs to: a node decides whether to forward or not the data packet depending on the value of this field and the state of its battery.

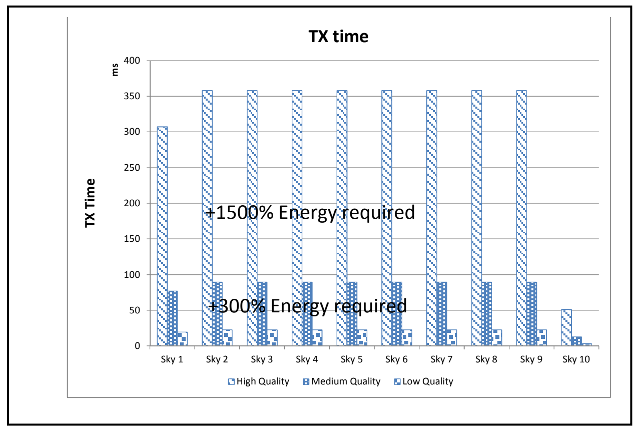

Fig. 11. High, medium and low quality required TX energy

Fig. 11 shows the energy spent by each sensor to forward the three different levels of image quality: for an uncompressed image, an additional 300% of energy is required to forward the MEDIUM QUALITY image compared to the LOW QUALITY image; this gap jumps to +1500% when comparing HIGH QUALITY and LOW QUALITY images. This priority level forwarding mechanism presents a limitation though: each mote decides whether to forward or not a certain packet depending exclusively on its battery status, without taking into account the battery status of the other motes along the path. What might happen is that some nodes will forward packets that will never reach their destination since nodes along the way to the destination have not enough energy to forward them, thus causing a useless waste of energy. To give an idea of how much energy might be wasted, we consider the worst case scenario: with reference to the topology shown in Fig. 13, we suppose node #9 having enough energy to only forward the LOW QUALITY image, while all the other nodes have enough battery to forward up to the HIGH QUALITY level. What happens is that the destination (node #10) will receive only the low quality image (LL2 sub-band) while nodes 1 to 8 have forwarded all the sub-bands. This leads to a +1333% energy spent than the simple sending of the LOW QUALITY image, as shown in Fig. 12.

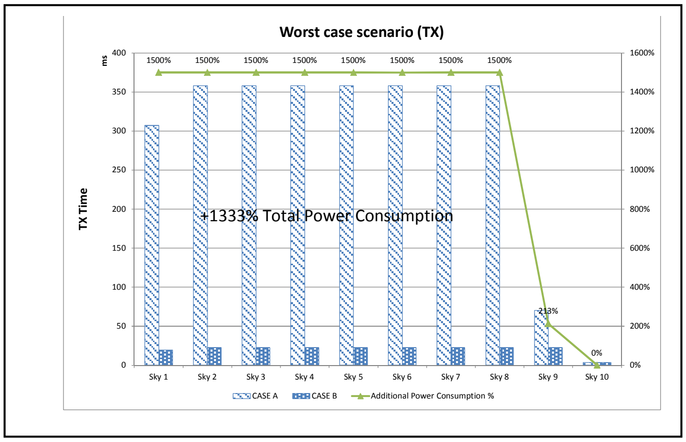

Fig. 12. Worst case scenario.

To overcome this limitation, each node receiving a packet to forward sends an ACK (Fig. 13) containing in addition to the reference to the received packet (Image ID and Data Offset) a field containing the Minimum Battery detected along the path in the network: each time a node receives an Acknowledgement it compares the Min Battery value received with its known value; if the new value is lower than the local known value, the local one is updated.

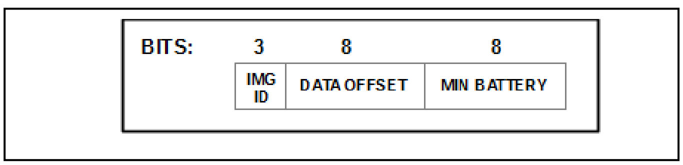

Fig. 13. Acknowledgment packet structure

Each node now decides whether to forward or not a packet not only depending on its battery status, but also taking into account the known minimum battery level of the network. Fig. 14 shows energy consumption for both feedback and no-feedback models.

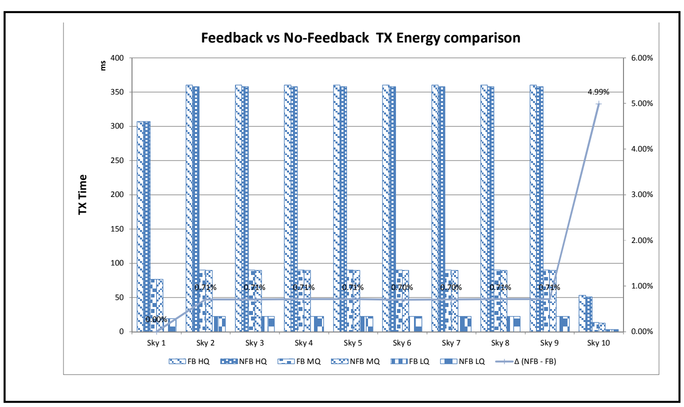

Fig. 14. Feedback vs No-Feedback TX Energy Consumption.

The average additional energy consumption introduced by the use of the feedback field in the acknowledgment packet is about 0.71%.

A. *Multipath Support In Image Delivery*

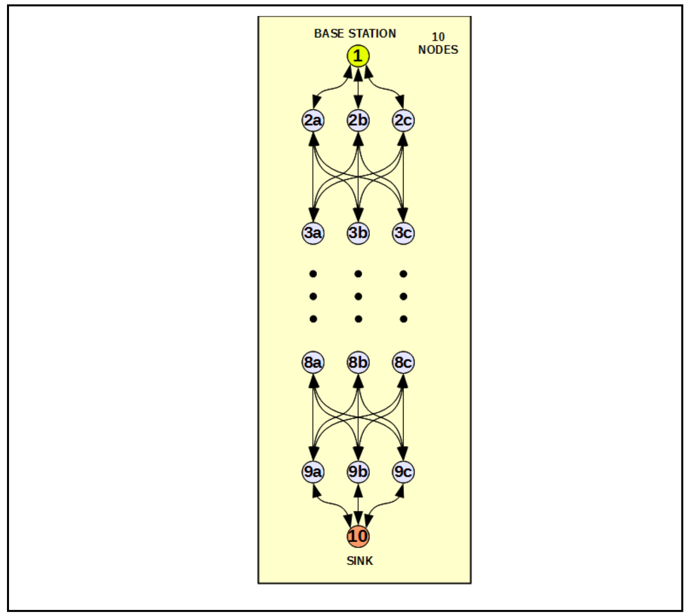

Fig. 15. Multipath topology.

The topology in fig. 9 shows only one possible next-hop destination for each node. Real networks may offer multiple paths to get to the destination. Topology shown in fig. 15 offer three possible next-hop nodes for each mote, instead. A sensor may choose which node forwards the data to, depending on the minimum battery level received from that node. At least two strategies are possible using the feedback support:

1. All data is sent to the node with maximum minimum energy available

2. Data packets are split through different nodes according to their priority and the node charge level

Option 2 permits a greater number of images to be sent with the highest quality available: if only the lowest priority packets are sent through the most highly charged sensor, the network will be able to deliver high quality images for a longer period of time.

B. *Compression Effect in Energy Consumption*

The use of DWT makes several levels of quality available for a given image, typically L+1 levels with L being the DWT order. Another feature of the DWT is that the detail sub-bands (HL, LH, HH) contain data in highly redundant form; for this reason compression of these sub-bands gives excellent results. To further reduce the bandwidth usage, a simulation was run using the LZW lossless compression algorithm applied to the different sub-bands. Results are shown in Fig. 16.

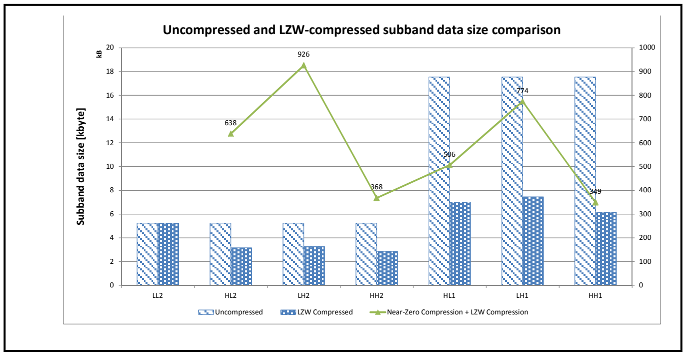

Fig. 16. Compression results.

As the graph shows, since the LL2 sub-band contains almost no redundant data, no advantage is taken in performing LZW compression on this sub-band. Compressing the 2nd level detail sub-bands gives a reduction of about 40% of data usage; compression of 1st level detail sub-bands allows a reduction of up to 65% of data usage.

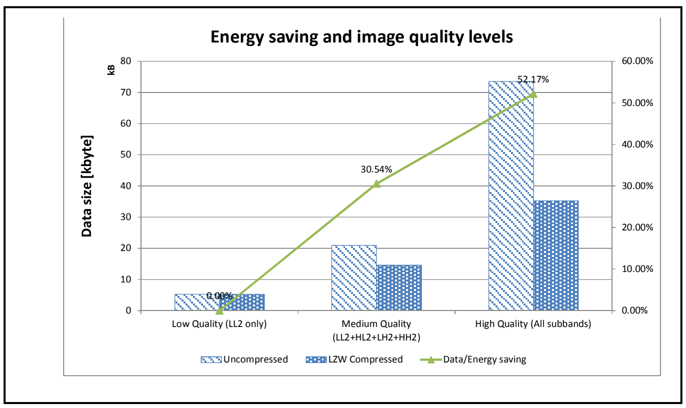

Fig. 17. Data Size and Image Quality.

Hence performing the LZW compression on the detail sub-bands allows a total 30.54% data reduction for the medium quality image and 52.17% data reduction for the high quality image (Fig. 17).

IV. Conclusion

Several ways of performing the Distributed DWT have been discussed in this paper; the best results for TX and RX time have been achieved with the 2 tier with tiling mode. To further improve these results a load balancing protocol with sleep mode have been introduced. For the image delivery task a protocol optimizing image quality while maximizing network lifetime has been considered.

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