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The Effect of Image Compression Technique on Wireless Sensor Networks

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Abstract

Recently, wireless multimedia sensor networks (WMSNs) have presented a significant advancement in multimedia applications. However, the transmission of video or images poses unique challenging issues if compared with sending simple signals, due to sensor nodes' resource limitations, in terms of processing unit specifications, memory, and energy consumption. This research analyzes the effect of transmitting images over low power wireless personal area networks using Internet Protocol version 6 (6LoWPAN), by presenting a new image compression algorithm (AriNib) by utilizing arithmetic coding with a proposed lossy approach that incorporates a modified Niblack thresholding operation to reduce the transmitted image size. As a result, the proposed algorithm lowered the network load and increased its lifetime due to the significant reduction of the consumed energy. AriNib compression algorithm demonstrated efficient image quality with PSNR value about 30 dB, achieving a compression ratio of 2 and a, presenting a promising performance in 6LoWPAN, by reducing transmitting time and consumed energy up to 50% compared to sending the raw image.

Keywords: WMSNs, 6LoWPAN, Image compression, Thresholding, Quality metrics.

تأثير تقنية ضغط الصور على شبكات المتحسسات اللاسلكية

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الخلاصة

في الآونة الأخيرة شهدت شبكات المتحسسات اللاسلكية للوسائط المتعددة (WMSNs) تقدماً كبيراً في تطبيقات الوسائط المتعددة. بالرغم من ذلك تواجه عملية نقل ملفات الفيديو والصور بعض المشاكل الصعبة اذا ما تم مقارنتها مع عملية نقل إشارات بسيطة، وذلك بسبب محدودية موارد أجهزة التحسس اللاسلكي من حيث خصائص وحدة المعالجة و الذاكرة والطاقة. مما يؤثر سلباً على أداء شبكات (WMSNs). هدف البحث تحليل تأثير ارسال الصور عبر تقنية شبكة النطاق الواسع منخفضة الطاقة باستخدام بروتوكول الانترنيت الاصدار السادس (6 LowPAN). يقدم هذا البحث خوارزمية جديدة مقترحة لضغط الصور (AriNib) من خلال استخدام طريقة التشفير الحسابي من نوع التشفير بفقدان يتضمن استخدام تعديل لعتبة Niblack لتقليل حجم الصورة مما سيؤدي الى تقليل الحِمل على الشبكة وإطالة عمرها بسبب الانخفاض الكبير في الطاقة المستهلكة لنقل الصور. انتجت خوارزمية ضغط الصور AriNib صور ذات جيدة مع تحقيق نسبة ضغط

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تصل الى 2 مع نسبة مقياس PSNRوصل الى dB30 كما أظهرت الخوارزمية اداءً واعداً في شبكات 6LowPAN حيث قللت وقت الارسال والطاقة المستهلكة الى 50% مقارنة بأرسال الصورة الاصلية.

1. Introduction

In the last few years, the industry of smart devices has witnessed significant growth along with the development in wireless sensor networks (WSNs) technology, which is a collection of nodes implementing sensors that collect distributed data, then transmit it wirelessly to the main node [1]. The main components of the basic wireless sensor nodes include a sensing unit, a microcontroller (for data processing), sensors (for sensing), a radio system (for communication), and the power source [2]. A wireless sensor node equipped with a digital camera and microphone, called wireless multimedia sensor network (WMSN), that is networks consisting of wireless embedded devices that can retrieve video and audio streams, still images, and scalar sensor data from the environment[3]. The multimedia data is very complicated if compared with sending a simple signal, therefore the WMSN has unique image processing and transmission challenges, due to the sensor platforms' architecture and the inherent resources constraints that are related to the power consumption, communication bandwidths, and processing capacity [4]. These limitations restrict image processing algorithms and transmitting high quality images. Moreover, the characteristic of the wireless protocol influences transmission limitations. The available wireless sensor technologies, such as Wi-Fi, Bluetooth, Zigbee, and 6LowWPAN, each possess distinct specifications, in terms of the wireless technology transmission range, data rate, power consumption, security, etc., studies on WSN types and their applications are explained in [1]-[3] .

The WMSN camera sensors are commonly powered by irreplaceable and unsearchable batteries [4]. In general, the primary batteries are easy to replace and less expensive compared to other power resources such as solar. The lifetime of a sensor node may be hours or years, determined by the power source and the amount of sensor consumed energy, a survey in [5] present a comparison of the lifetime of common commercial nodes powered by the batteries. Capturing and transmitting video streaming for real-time applications is a challenging task due to the huge bit rate transition (video). Designing an image processing algorithm with good quality, suitable for the limited memory and processing capability of the sensor is another challenge.

Therefore, efficient image compression techniques are an essential solution to reduce the image size, which in turn will reduce energy consumption and transmission time. This solution is the main objective of this paper.

2. Related works

During the last decade, scientific research has been devoted to improving WMSNs performance, through several strategies including improving the platform’s capability, the communication and routing protocols with good quality of service (QoS) [4] , and building efficient software systems, which is the methodology of our research. However, before designing any application, the sensor mote characteristics and limitations must be considered, a detailed review presented in [6] showing the processing unit and radio transceiver features of the most commercial sensor motes. Another important standard is the network efficiency, such as the throughput, packet delay time, packet loss, which are explained and evaluated in [7] considering the most common protocols (6LoWPAN, Zigbee, Bluetooth) showing that 6LoWPAN has good throughput on WMSNs.

Prolonging the power source life is very important for WSN continuity, the authors in [8] discussed the recent research on WSN energy conservation, with emphasis on minimizing the radio energy consumption, since most of the energy is lost at the transceiver during data transmission, showing that one of the main solutions is to reduce the transmitted data size. These studies are considered in this paper to adopt the suitable protocol and transceiver device for efficient image transmission.

Recognizing that image size reduction and the number of transmitted video frames will reduce the power consumption and image transition time, many researchers suggested image compressing techniques tailored for multimedia sensor nodes. In [9], the authors proposed an image compression method for WMSNs using discrete wavelet transform (DWT) on the image with a lossless method applied as blocks, showing good compression ratio up to 1.
Another paper [10] applied a new block truncating coding BTC on a low power IOT chip, the method presents better results than the original BTC algorithm, with 33% improved performance. Skosana et al. in [11] reviewed some common compression algorithms, showing that discrete cosine transform (DCT) algorithm and DWT have the best performance for WSN in terms of energy consumption and computational complexity, but produce low image quality. Also, the authors in [12] compared DCT with WT on small satellites showing that using WT (bior 3.7) yields the higher compression ratio. While Kamatar et al. [13] proposed lossy image compression applied on image blocks, then eliminating 50% of the pixels of each block, the compression ratio on gray images is 2.

Lungisani et al. [14] proposed a block base image compression for WSN, using a lossy technique, the evaluation metric of image quality using PSNR was less than 30dB, showing that 50% of the energy consumption is conserved at compression ratio 60%. Boes et al. [15] technique is reducing the image data redundancy using spatial and temporal correlation. According to the resulting analysis, in case compressing the image by more than 70%, the PSNR drops to around 32 dB, while a compression rate of 38.6, reduced the consumed energy by 50%. In [16] Xuecai the authors proposed a segmentation based compressive autoencoder model (MS-CAE) for WSN, using deep learning and comparing the results with other methods, showing that the PSNR value about 23 at bit per pixel (0.1-0.2), but did not present the effect on the transmission time or the consumed energy.

The authors in [17] presented a survey on image compression using classic and deep learning methods, recommending the deep auto encoder for image compression. However, deep learning methods were excluded from this study due to their computation and memory demands, which exceed the resources limitations of the WMSN node.

The previous works on image compression methods for WMSN can be classified as a compromise of surveys with general comparison or suggest image compression methods but lack the evaluation of the compressed image size on the network efficiency as transmission time and consumed energy. This work aims to address these shortcomings, by applying a new image compression method based on a light classic method, then test the effect of the proposed method on WMSN using MATLAB code and a simulation tool.

3. 6LoWPAN / IEEE 802.15.4 wireless network

IEEE 802.15.4 standard [18] comprises to meet the needs of low-power wireless personal area networks (Lo-WPANs), which are used for WSNs. IEEE 802.15.2 standard defines specifications of scientific and medical radio frequency bands, operating at the common 2.4 GHz, which supports a data rate of 250 Kbps, as explained in IEEE 802.15.4 standard document [18]. 6LoWPAN technology is based on IEEE802.15.4, which integrates Internet Protocol version 6 (IPv6) with Lo-WPAN environments, a detailed description of standard explained in [19]. Packet transmission over the IEEE 802.15.4 standard uses carrier sense multiple access-collision avoidance (CSMA/CA) algorithms for channel clear assessment (CCA), and a detailed description of the algorithm in [18].

In this paper, the 6LoWPAN protocol is adopted, for image transmission as it offers reduced power consumption, improves robustness, is easy to analyze due to its low complexity, besides it has a low bit rate, short range, and low cost [20]. The maximum transmission unit size for IPv6 packets over IEEE 802.15.4 is 1280 octets [19]. While according to the IEEE 802.15.4 protocol document, the maximum physical layer packet size (aMaxPHYPacket) is 127 bytes, the data unit sizes depend on the packet overhead, if minimum overhead is used, considering the IPv6 and 6LoWPAN adaption features, the payload data size is 108 bytes[21] , which is good enough to work for image application and adopted in this paper.

4. Image compression

Image compression operation is very important for WMSNs due to its limitations (bandwidth, memory space, power source), where decreasing the image size will optimize the network efficiency. Image compression techniques are mainly classified into lossless and lossy compression. Lossless compression is when the compressed image can be retrieved perfectly, otherwise it is a lossy compression [22]. Lossless methods are used if the compressed image quality is important. While lossy techniques remove permanently parts with a small significance or irrelevant data of the image[23]. The benefit of lossy over lossless is that it has a higher compression rate [10].

The simplest method to remove data (pixel) is applying thresholding. Two steps are required to apply thresholding: first, determine a threshold value according to an objective criterion, second, assign the image pixels to one class of background or foreground [24]. The threshold value indicates the number of removed pixels that will affect the image quality and compression ratio; therefore, it is very important to apply the appropriate threshold value. Another technique to reduce the image data is the quantization operation applied on lossy compression, performed by dividing the original image range into a number of bins [22].Thus quantization operation causes some degradation effects on the image quality.

4.1 Image evaluation measurement

In order to evaluate the image quality after applying the proposed compression algorithm (AriNib), the most common metric, peak signal-to-noise ratio (PSNR), is used, which depends on the error signal by using the mean squared error (MSE). The unit of PSNR is the decibel (dB) which takes from 0 to infinity for high image quality. The equations of PSNR and MSE are given in [22]. Another adopted metric is the structural similarity index (SSIM), which is targeted at perceived structural information variation, instead of perceived error [25]. Applying image processing and lossy compression may lead to some changes in the pixel values where some sharp edges might become flat. Therefore, a blur metric is adopted as explained in [26], the metric value range is [0-1], which is the best and the worst quality of the variation between the original and the blurred image in terms of blur perception.

To evaluate the compression operation, the compression ratio (CR) is used to compare the size of image before compression and its compressed version [23]. After compression operation, the number of the image bits per pixel (bpp) will be reduced, getting less value means getting a higher compression ratio, the (bpp) equation is explained in equation (1) [10].

$$\text{bpp}=\frac{\text{total no.of bits of the compreesed image}}{\text{Number of pixels}} \quad (1)$$

5. Methodology

This research presents a new image compression technique and evaluates image transmission under WMSNs applications, the following explains the strategy:

1- Apply an image compression operation that integrates arithmetic coding with a proposed quantization equation and a modified thresholding operation. This technique aims to drop image pixels selectively to increase image compression ratio while preserving visual fidelity.

2- Select the packet size (payload) according to the 6LoWPAN protocol, then compute the number of packets for each image before and after compression operation.

3- Simulate the packets transmission over the 6LoWPAN protocol, before and after applying image compression technique.

4- Evaluate the compression algorithm in terms of image quality, compression metrics, and the network performance in terms of transmission time and energy consumed.

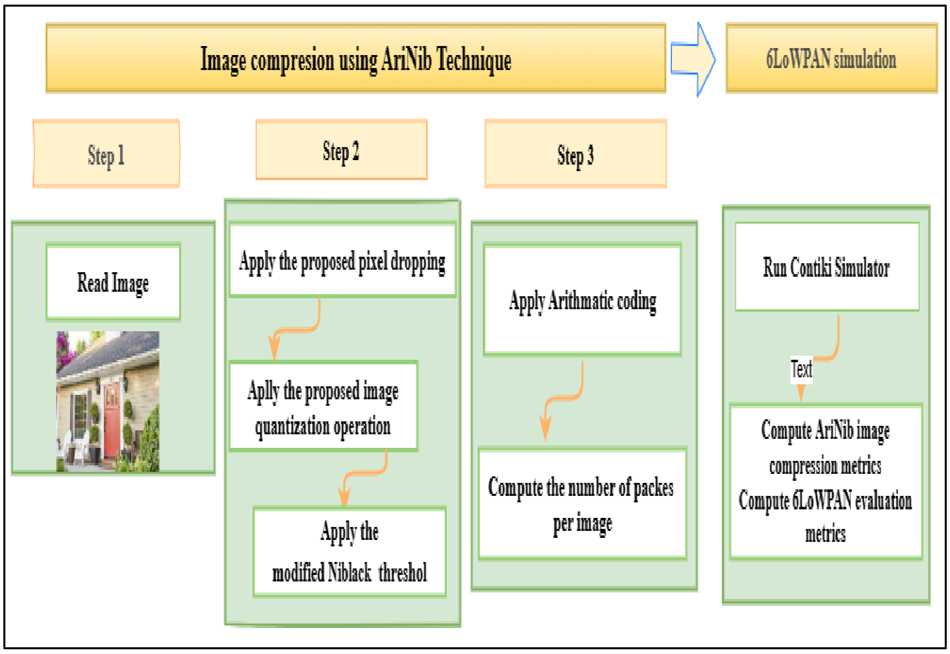

Figure 1: The proposed Methodology

6. The proposed image compression technique (AriNib)

The proposed image compression algorithm (AriNib) prioritizes simplicity to be compatible with the resource constrained sensor mote processor. AriNib algorithm utilizes lossless arithmetic coding, which depends on the data (pixel) occurrence and represents the data as a sequence of symbols determined by their probability[22] , this approach considers the image texture effectively. To increase the compression ratio, we proposed a pixel dropping technique that was achieved by designing two steps. First apply a quantization operation on the input image to reduce the number of distinct pixel values. This reduction will lower the image size, computation, and memory requirements, which is critical for wireless sensor node limitations. The proposed quantization value (Qvalue) explained in equation (2):

$$\text{Qvalue} = \text{round}((\log 2)\text{abs}(\text{round})\text{mean}(\text{image})) \quad (2)$$

This equation was developed through practical experience to increase the compression ratio and preserve the image quality. The equation balances the Qvalue using the absolute image mean value rounded to the nearest value, then the base 2 logarithm (log2) is applied to get smooth image details. The second step involves applying a thresholding operation to remove unnecessary pixels, which is a very critical step since the compression ratio and image quality depend on this value, where selecting a high value will increase the compression ratio but degrade the image quality, to fulfil the aim of AriNib algorithm we adopted Niblack thresholding method [27] Niblack's strategy is applying the threshold on image local areas (blocks), by calculating the mean and the standard deviation, which considers the image pixel intensity that will help to preserve the image lighting and details, moreover a factor (k) used to increase or decrease the value of the threshold value providing flexibility to be suitable for different applications. The following equation (3) describes Niblack thresholding [27]:

$$T(x,y) = m(x,y) + K \times s(x,y) \tag{3}$$

Here T(x, y) is the threshold value of a local area, while m(x, y) and s(x, y) respectively, are the mean and the standard deviation of a local area, and (k) is a variable.
The AriNib algorithm modified the Niblack threshold by addressing two issues. First, it introduces a weight value (*w*) to Niblack's equation which aims to improve the compression ratio and preserve the image texture. Second, instead of applying the threshold on local image blocks, it utilizes a global threshold value derived from the entire image I (n, m). This adjustment is adopted to avoid blocking artifacts that occur in local thresholding. Hence the proposed modified Niblack equation is:

$$T= m(x,y) + K \times s(x,y)^{w} \tag{4}$$

Where T is the threshold value for the entire image, (w) and (k) are variables.
The stage of AriNib algorithm is applying arithmetic coding to compress the image. The empirical results show that the (*w*) value in the range (0.8 to 0.99), and (*k*) value between (0.2 and 0.3), yield the best compression ratio. However, selecting the (w) value depends on the required image size and quality, for example, using w=0.8 produces a good image with a low compression, while increasing the (k) value improves compression but decreases the image quality. Algorithm 1 explains the proposed compression algorithm (AriNib).

Algorithm1. The proposed image compression technique (AriNib):

Input: read the raw image (I)
Begin
    Compute the quantization value of the image (I) using equation (2)
    Get the threshold value (T) of (I) using the modified Niblack threshold in equation (4)
    For each pixel in the image (I) do
        If pixel value < T then
        set the pixel value to zero
        End if
    End for
Apply arithmetic coding on the image (I)
Output: a compressed image and the quantization value
End

On the receiver side, image decompression will be performed by applying arithmetic decoding on the compressed image and then applying a dequantization operation by multiplying the image with the quantization value to restore the original image.

7. LoWPANS network simulation

To analyze the effect of image compression process on WMSNs, a comparison of two transmission scenarios is applied, first sending the raw image from the camera node to the server, second, sending the image after applying the proposed (AriNib) algorithm. Analyzing and evaluating image transmission wirelessly requires a simulation platform compatible with the adopted network protocol specifics. Contiki OS Power tracer is a network level power profiling system for low-power wireless networks[28]. It supports many platforms and WSN protocols. Contiki with Cooja is adopted in this paper to evaluate packet transmission time and energy consumption, since it provides IPv6 for sensor nodes connectivity and 6LoWPAN protocol.

7.1 Image transmission measurements

To simulate image transmission over WMSNs using 6loWPAN protocol, the Tmote Sky platform is adopted, which is a low-power sensor used for wireless sensor networks using IEEE 802.15.4 standard with 2.4GHz Chipcon wireless transceiver and 16-bit RISC processor [29]. The mote has extremely low active and sleep current consumption that permits it to run for years on a single pair of AA batteries as explained in the platform datasheet[29]. The proposed simulation parameters explained in Table 1.

Table 1: Contiki Simulator parameters

Setting Parameter	Value
Camera node type	Tmote Sky platform
Platform hardware timer is	32768 Hz
Wireless standard	IEEE 802.15.4 with 2.4GHz
Network Protocol	6loWPAN
Network topology	point to point
Transmission range	50 m
Packet data size	108 bytes
Simulation time	One hour
Initial battery energy	2000 mAh

The time interval to transmit a packet (Tx) and receive (Rx) acknowledgment packet (Tack), besides the protocol delay time, are computed according to the Tmote sky platform with IEEE 802.15.4 and CSMA/CS steps. Considering Contiki 3.0 OS simulation, the time required to transmit a packet is presented in equation (5) according to [30]

$$\text{Time} = \text{Tdata} + \text{turnaround time} + \text{Tack} + \text{Twait} \quad (5)$$

Where (Tdata) is the data packet transmission time, (Tack) is acknowledgment packet receiving time, (Twait) is the sender wait time, while the turnaround time is needed by the sensor node to switch the transceiver from receive to transmit mode and vice versa[18]. There are some waiting times related to IEEE802.15.2 access mode and the CSMA-CA algorithm, explained by Kashoash[30]. The transmission model in this research assumes a continuous process of sending data packets and receiving ACK packet, thus the turnaround time for (Tdata) is added to equation (5) which is the time to switch from receive mode to transmit mode as explained by the IEEE802.15.4 standard document[18]. So, equation (6) for packet transmitting time will be:

$$\text{Time} = \text{Tdata} + \text{turnaround time} + \text{Tack} + \text{turnaround time} + \text{Twait} \quad (6)$$

According to Dunkels et al. [28].Energy measurements for a sensor node include the time spent at each power state during the communication process. The sensor state includes (transmit, receive, idle, and low power mode (LPM) [31]. These activities are provided by the Contiki powertrace. Equation (7) presents the system power consumption according to [28].

$$E_{system} = \sum_{m,n} P_{m,n} T_{m,n} \quad (7)$$

Where (P) and (T) respectively represent the power and the run time of each component (m) during the state (n). Example of node components (CPU, radio, memory, camera sensor). In this paper, power consumption for image transmission, computed considering the ACK packet receiving time, adding to it the turnaround time to switch from Rx to Tx mode according to IEEE 802.15.4 standard[18]. The same for TX mode, which is already considered in equation (6), where the LPM (sleep) time during CCA process is 1.7 ms [31]. According to [32]the total energy consumption of a sensor node is calculated using equation (8) considering the time spend by the radio states (transmission (TX), listen or (RX), CPU time and sleep) multiplied by the power value of each state which is provided by Tmote Sky datasheet, where the hardware timer is 32768 Hz[29]. Equation (8) represents the sensor consumed energy during the active state[32] .

$$Energy(mj) = \frac{(Transmit \times 19.5mA + Listen \times 21.5mA + CPU \times 1.8mA + LPM \times 0.0545mA) * V}{32768} \quad (8)$$

It should be noted that, (listen) power according to Tmote datasheet is 21.8 mA (used in this study), which is a little higher than the number used by [32] in equation (8), which is (21.5 mA).

8. Results and discussion

The proposed (AriNib) compression algorithms, and the evaluation metrics are implemented using the MATLAB 2022a programming environment. The experimental test included grayscale and color images with different textures to show the effect of compression operation on the image quality. All images are of size (265*256), the gray images (Goldhill, pepper) of type 8 bits, where the original image size is (46 KB), while the colored images (window, parrot) are 24-bit of type RGB, with image size (129 KB). Figure (2-a) presents the original images and Figure (2-b) the resulted images after applying the proposed algorithm (AriNib), it is clear that the resulting image visual quality is very good and smooth, with a bit of degradation in terms of blurring, which is a common effect of image compression operation. There is almost no blocking effect due to the application of the appropriate threshold found from the image using the modified Niblack and quantization method.

Figure 2: Compression results: (a) Original images (Goldhill, pepper, window, parrot); (b) the result of applying (AriNib) algorithm.

The next Figure 3(a) explains the objective evaluation of the (AriNib) algorithm in terms of image quality. The PSNR value is normalized to 10, the highest PSNR value of image (peeper) is 23 dB, the MSSIM metric for all images is close to 0.8, while the blur metric is very close to zero. All these values are very good for image quality evolution. The (AriNib) compression algorithm evaluation metrics presented in Figure 3(b), the compression ratio of image Goldhill is a little higher than other images, the (bpp) has almost a close value for the images, from these values it is obvious that the AriNb algorithm reduced the image size to about 50%. In terms of execution time, it is the highest (about 5 seconds) for color images due to its large image size, which consists of three images (Red, Green, Blue).

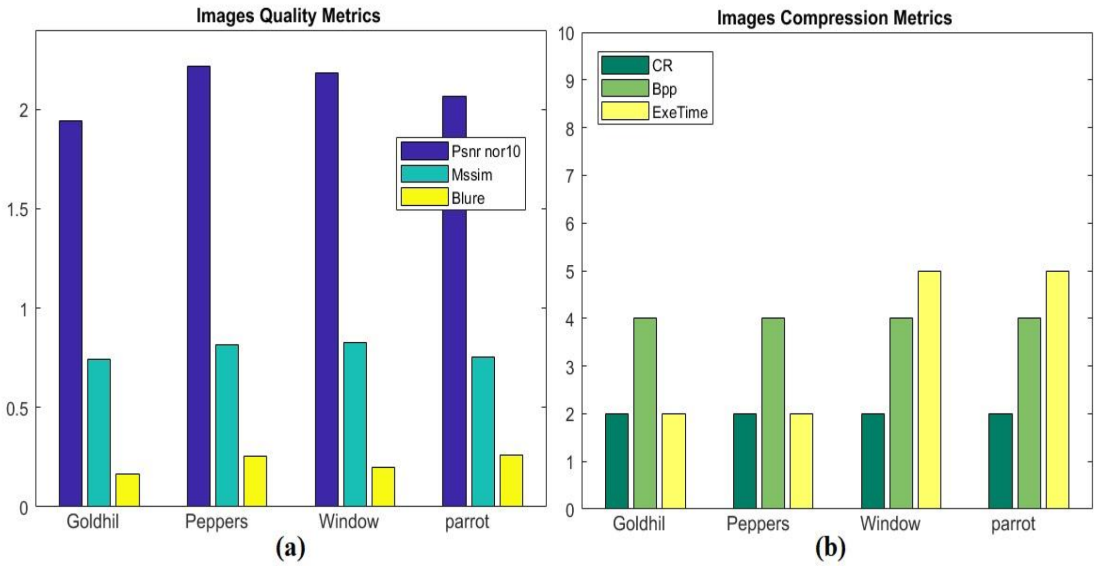

Figure 3: Compression evaluation: (a) Image quality metrics; (b) Performance of (AriNi) algorithm

Figure (4) explains 6LoWPAN network metrics for image transmission. First, the number of the packet of the original images (OrgImag) and the compressed image (CompImag) are computed, assuming the payload size is (108) bytes as the optimal case. The results show that the number of packets of the compressed image is about 50% less than the original image due to the very good performance of the AriNib compression algorithm to reduce the image size, which in turn reduced the image packets transmission time (CompImTime) and its consumed energy (CompImEnergy). For example, to send the colored image (parrot), the transmission time over 6LoWPAN wireless network using IEEE802.15.4 protocol requires about 16 seconds, and the consumed energy is about (29.15 mJ), these numbers were reduced to (8.40 sec. and 15.10 J) after applying the AriNib algorithm, leading to increase in the power source lifetime and obtaining sustainability especially for WSNS limited energy power source

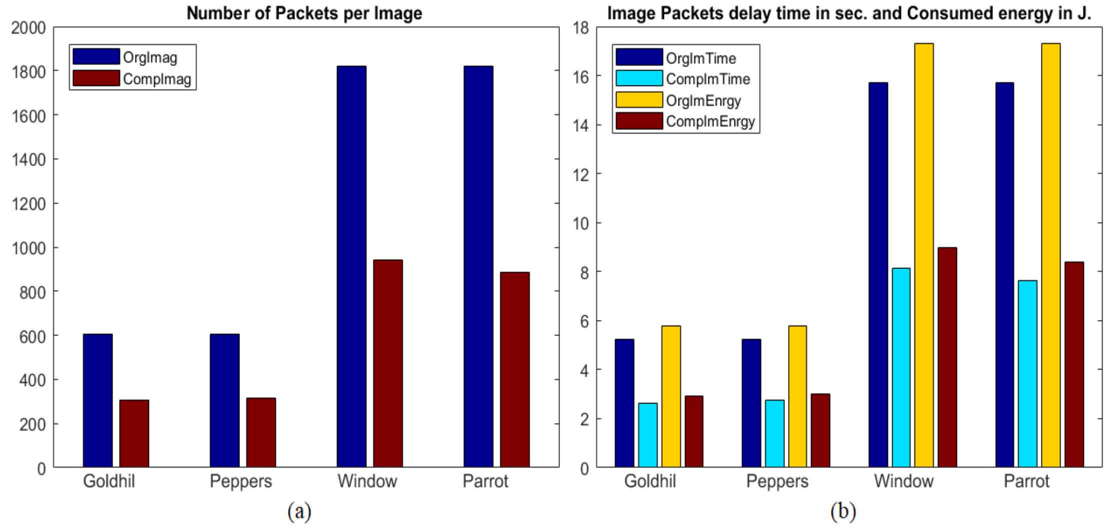

Figure 3: The AriNib algorithm resulted in metric: (a) Image packet number (b) image transmission delay time and consumed energy of the origin and the compressed image

Despite the numerous studies in this field, the majority have focused on compression ratio without mentioning the actual network performance metrics. Table 2 presents a comparison with some previous works, showing efficient performance of AriNib technique.

Table 2: Comparison among previous work

Reference	Image metrics	Energy
[13]	CR=2, PSNR 33-44	N/A
[14]	PSNR less than 30 dB at 0.2 bpp	Reduced to 50% at CR=60%
[15]	PSNR 32 dB at CR more than 70%,	Reduced to 50% at CR=38.6 %
[16]	PSNR about 23 at bit per pixel (0.1-0.2)	N/A
Proposed AriNib	PSNR average 22 at CR 2.1	50%

9. Conclusions

In this paper a new hybrid image compression strategy (AriNib) is proposed, combining the traditional arithmetic coding with a suggested quantization processes and a modified Niblack threshold with adopted parameters that were empirically optimized to balance compression efficiency (achieving 50% image size reduction) and the perceptual image quality, which are validated via (PSNR, SSIM and Blure metrics), demonstrating good performance and confirming visual acceptance. AriNib optimization on image size, reduced the processing and memory requirement due to eliminating unnecessary pixels, which directly improved the network efficiency by reducing the transmission time and consumed energy about (50%), hence extending the lifetime of the wireless sensor network, which is a critical

factor for its constrained recourses. Additionally, the network analysis in this paper was conducted by using Contiki OS environment, offering precise modelling of packets transmission and power consumption pattern. This work bridges the gaps in current WMSN research, by introducing compression innovation and IEEE 802.15.4 with 6LoWPAN co-analysis of protocol and platform and establishing a foundational framework for future energy-aware multimedia transmission, to both WMSNs and general internet-based transmission system.
Future work will aim to develop a deep learning compression algorithm that dynamically increases the compression ratio depending on the remaining battery energy. Analyz the algorithm on different network topology.

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Conflicts of interest
The author declares no conflict of interest

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