Digital Communications and Networks 5 (2019) 131–137

Contents lists available at ScienceDirect

Digital Communications and Networks

journal homepage: www.keaipublishing.com/dcan

Field test of multi-hop image sensing network prototype on a city-wide scale

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ARTICLE INFO

Keywords:
Image sensing
Prototype
Field test

ABSTRACT

Wireless multimedia sensor networks drastically stretch the horizon of traditional monitoring and surveillance systems. Most existing research has utilized Zigbee or WiFi as the communication technology. Both technologies use ultra-high frequencies (primarily 2.4 GHz) and suffer from a relatively short transmission range (i.e., 100 m line-of-sight). The objective of this study is to assess the feasibility and potential of transmitting image information using RF modules with lower frequencies (e.g., 433 MHz) to achieve a larger-scale deployment as in a city scenario. The Arduino platform is used because of its low cost and simplicity. Details of hardware properties are provided in this article, and we investigate optimum configurations for the system. After achieving an initial range test transmission distance of more than 2000 m line-of-sight, the prototype network is installed in a real life city plot for further examination of performance. A range of suitable applications is proposed and suggestions for future research are provided.

1. Introduction

Wireless Multimedia Sensor Networks (WMSN) have been an attractive topic of dedicated research and development in recent years. A WMSN enables sensor nodes equipped with a camera and/or microphone to provide direct and authentic information to end users. WMSNs considerably extend the horizon of traditional monitoring and surveillance systems. Akyildiz [1] explained that a WMSN can be used for a great variety of applications, including multimedia surveillance sensor networks, activity storage, traffic avoidance and control, family and health care, environmental monitoring with acoustic and video feeds, personal locator services, and industrial process control. The productive concept models proposed by researchers have led to a new era of pervasive sensing networks that are highly mobile and flexible.

The fundamental components of WMSNs are networked stations implemented to retrieve video and audio streams as well as still images. The rapid advancements of hardware development in the IT industry have quickly made this a reality. One example of a new hardware development is Complementary Metal Oxide Semiconductor (CMOS) image cameras that can function as image sensors for data collection [2]. In general, this type of image sensor can capture both BitMaP (BMP) and Joint Photographic Experts Group (JPEG) encoded images, although JPEG images generate less data information for transmission over the network.

Most existing wireless communication technologies for WMSN typically use either Zigbee or WiFi technology with ultra-high frequencies (mainly 2.4 GHz). However, the transmission ranges for Zigbee and WiFi are limited to a localized area, with Zigbee being restricted to approximately 100 m [3] and WiFi to less than 100 m outdoors [4]. Therefore, the network deployment scope is relatively confined by the transmission range. For example, despite the different application scenarios of research as given in Ref. [5], a typical 30-m transmission range was assumed for its simulation work. Although 400 nodes were employed, this large number could only cover a total area of 400 × 400 m, which is a typical dimension of a business location. For the purpose of cost-effectiveness and ease of management, nodes should be deployed with less density and a longer transmission range between adjacent nodes in order to cover a relatively large network area.

The aim of this research is to explore the possibility of deploying a WMSN on a city-wide scale. Lower frequencies are used to expand the potential transmission range, and the feasibility of network deployment with optimum system settings is assessed in a field test. The 433.050–434.790-MHz band with a center frequency of 433.920 MHz is chosen for the text and image transmission tests. This is a license-free Industrial Scientific Medical (ISM) band established by the International Telecommunications Union (ITU) and can be used for industrial,

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https://doi.org/10.1016/j.dcan.2017.07.002
Received 2 June 2016; Received in revised form 16 May 2017; Accepted 4 July 2017
Available online 6 July 2017

scientific, and medical purposes. Currently, this frequency band is mostly utilized for point-to-point wireless communications with low data flow or for traditional Wireless Sensor Networks (WSNs) such as remote meter reading systems.

The sensor node prototype is built on Arduino, which is a flexible and user-friendly electronic platform with an open-source scheme that includes the sharing of knowledge at both the hardware and software levels [6]. The Arduino product has experienced dramatic growth over the past few years because of its simplicity, cost effectiveness, and low-power consumption features. Currently, Arduino has been widely used as the development platform for sensor networks because of its low cost, high usability, and popularity.

The significance of this research is not only in proving the feasibility of deploying a multi-hop image sensor network on a city-wide scale, but also in contributing to research on the use of off-the-shelf devices. Academic studies that employ off-the-shelf products can offer a range of benefits compared to bespoke systems, including a variety of choices, full testing by many existing users, immediate availability, ease of upgrade and customization, relatively low developmental cost, and a wide range of support from the user community. In today's ecology of multidisciplinary research, groundwork experiments based on off-the-shelf systems can offer immediate and effective solutions for practical applications. Particularly with respect to image sensing scenarios, the results of this study offer advanced ideas for smart city deployment using low-cost hardware that requires minimum training and can be easily scaled (in terms of both quantity and physical dimensions) in a city scope.

Section 2 explains the system implementation, including both the hardware prototype and software settings. Section 3 presents the initial test results, including for range, data rate, and power consumption. Section 4 demonstrates the details of our outdoor experimental setup and results. Section 5 suggests suitable applications for the designed system. Section 6 concludes the study and suggests ideas for future work based on our research.

2. Prototype

2.1. System setup

The image transmission approach adopted for this study is to capture an image, decompose the image file into an array of pixel data, transmit the data though an RF module, and save the image to an SD card. Future research can develop additional end-processing software to enable received images to be displayed live on a monitor. Fig. 1 shows the schematic for a sensor station employed in this study, which is equipped with an Arduino board, camera, RF module, and battery.

Fig. 2 shows the actual hardware prototype built in accordance with the schematic shown in Fig. 1. Four of these prototype stations have been built with manually configured cross-layer addresses. The use of batteries is flexible: they can be either AA alkaline batteries commonly available in the market or a USB-based battery pack. The technical specifications of the system are summarized in Table 1.

2.2. Microcontroller

Considering the numerous products in the microcontroller market, Arduino offers unique advantages over its rivals. The hardware

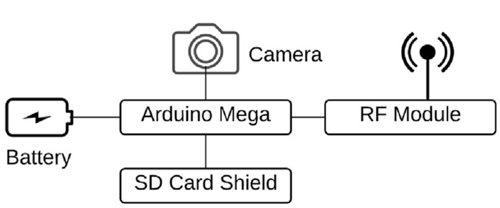


Fig. 1. System schematic.

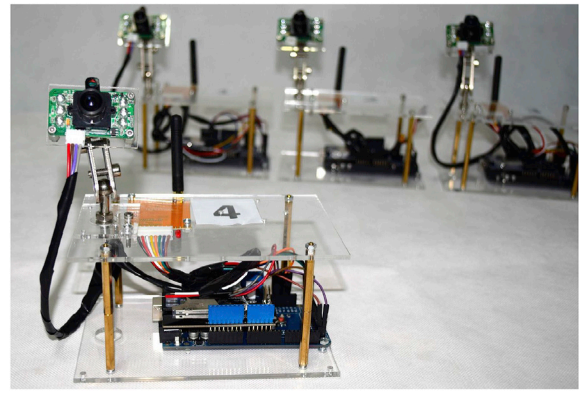


Fig. 2. Image sensor node prototype.

Table 1
System hardware specifications.

Arduino Mega	Processor	ATmega2560
	CPU Speed	16 MHz
	Analog I/O	16/0
	Digital I/O	54/15
	UART	4
	SRAM	8 KB
RF Module	Serial Port Data Rate	Up to 57,600 bps
	Transmission Data Rate	Up to 19,200 bps
	FIFO Buffer Size	Up to 256 bytes
	Transmission Power	Up to 20 dBm
	Modulation	GFSK
Image Sensor	Serial Camera	320 × 240

requirements of this research project include low cost, simplicity, a large library of functions, a wide range of learning community resources, and most importantly, efficient power consumption, all of which Arduino delivers. In the field of Internet of Things, Arduino, Raspberry Pi [7], and Beaglebone [8] are often compared for use as alternative electronic boards for a variety of applications [9]. Although the last two may offer some features that cater to the needs of our research, they do not satisfy all the criteria previously mentioned. In particular, despite the high specifications of both Raspberry Pi and Beaglebone, they require a constant supply of power, and batteries are not an ideal option. This can largely compromise the portability of the system, and thus these products are not desirable for use with the wireless sensing network scenario of this research.

Various models and options are available in the Arduino family. Arduino Mega was chosen for our study because of its built-in specifications. Compared to other Arduino models, the greater number of I/O interfaces and universal asynchronous receiver/transmitter ports on the Mega model make the system implementation relatively future-proof and easy to scale, as more features can be easily added to the application. One of the limitations of the Arduino family of products is the shortage of extended high-performance capabilities, and when networking or image processing is to be enabled on Arduino, a shield to interface a separate functional hardware module is often required. In this case, an SD-card shield must be installed on the sensor station. In transmission mode, images are saved to the SD card temporarily before wireless transmission. In receiving mode, the SD card is simply used for storage.

2.3. Image capturing

The research in Ref. [10] compared the transmission of BMP and JPEG format images. The latter produces sufficient image quality with shorter latency, which is required in our system. JPEG images can be captured by either ArduCam [11] or serial port cameras, which produce average file sizes of 6–8 and 11–14 KB, respectively. The image sensor for the hardware prototype is a serial port camera module. This is chosen because the image compression of the system is lower than ArduCam, delivering image files with more details and information that can be transmitted directly to the Arduino board through a serial communication port. The model used in the image sensor module is OV2640 because of its high popularity and availability [12]. The resolution of the captured JPEG image is QVGA 320 x 240.

2.4. Communication

The RF module employed in the system is highly integrated, operating in half-duplex mode and connecting to the Arduino board through a serial interface. It uses a GFSK modulation to provide multiple channel options and is equipped with a first-in-first-out buffer. The serial port rate, transmission power, RF rate, and other parameters can be configured using software.

At the first research stage, the transmission process is point-to-point and one-way, and the transmitter and receiver nodes are programmed separately. For the transmitter node, a loop is used to read the image file and forward the data. This includes the process of reading a byte from the camera's buffer, adding the byte to an image string, and then proceeding to the next byte. At the end of the file processing loop, a frame footer is added to the image string, which is then sent to the serial communication port. An appropriate delay is added as a guardband during the transmission process. The program for the receiver node is very similar to that of the transmitter node, which also includes a loop for processing the image file, with one byte read by the serial port each time. The loop ends when it reaches the frame footer byte, and the image string is consequently saved to the SD card.

Unlike BMP files, JPEG-encoded images of the same resolution may not necessary have the same file size. Thus, a fixed-length loop cannot be used to transmit JPEG files. A standard JPEG file always begins with FF D8 in hex and ends with FF D9. A control protocol is programmed at the transmitter end to read continuously the JPEG file until hex FF D9 is detected, indicating the end of the file. The file can still be divided into packages of fixed length, although the last package may be shorter. Given the buffer size of 256 bytes, 240 bytes are used as the fixed length for the image file transmission in this system, which leaves sufficient room for header and interval bands. The following is an example of a transmission sequence in a JPEG file:

```
FF D8 XX XX... XX XX XX XX (240 bytes)
XX XX XX XX... XX XX XX XX (240 bytes)
...... ......
...... ......
XX XX XX XX... XX XX XX XX (240 bytes)
XX XX... XX XX FF D9 (100 bytes)
```

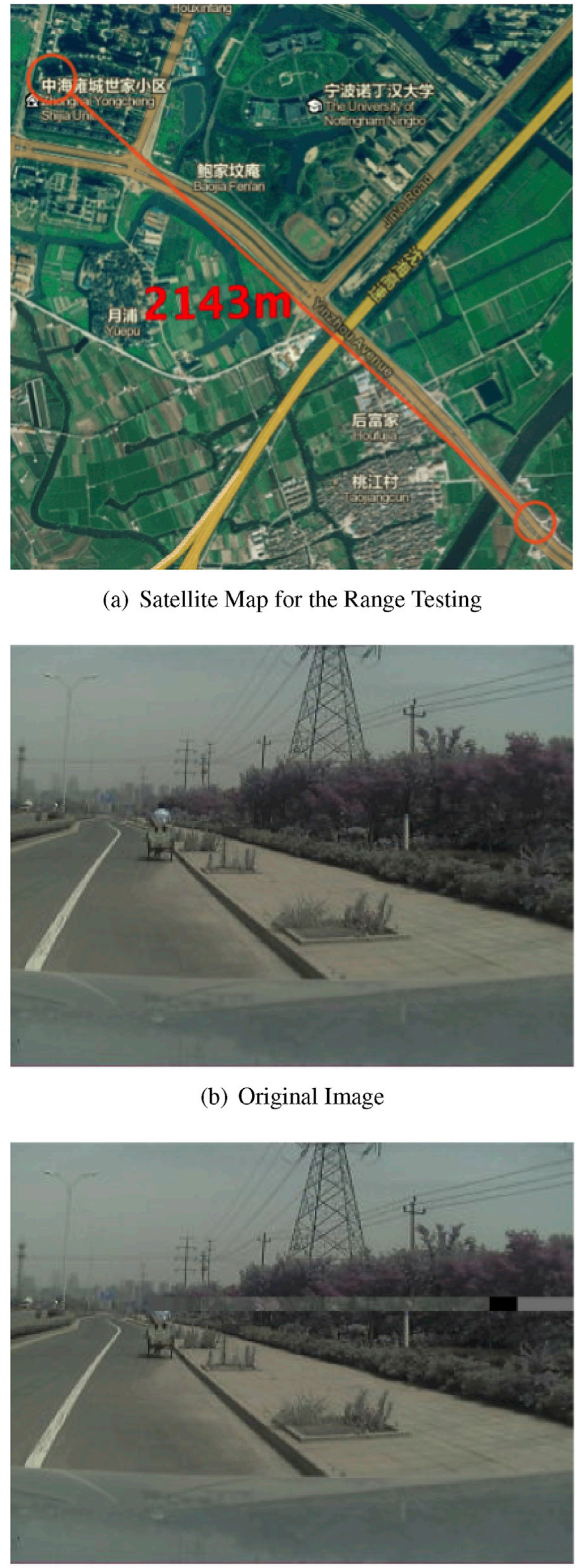
The receiver is programmed to stop receiving data once hex FF D9 is detected. This is necessary in order to adapt the uncertainty of the file size. Because of the lossy compression algorithm used in JPEG images, monochrome areas are normally expected [13], although the study in Ref. [10] indicated a satisfactory image quality.

3. System measurements

3.1. Range testing

As previously mentioned, one major advantage of the designated system is a long transmission range. To verify this capability, a transmitter station was placed at a location having GPS coordinates of (N29.80128°, E121.55468°) with a high altitude to ensure a clear transmission path and thus enable line-of-sight signal testing. A receiver station was installed in a moving vehicle travelling along a divided highway. The air quality index of the day was 178, indicating moderately polluted air.

The transmission range limit was found when the receiver reached the coordinates of (N19.79132°, E121.56602°), as displayed in Fig. 3(a). Within this range, all received images were close matches of the transmitted images. Fig. 3(b) and (c) compare the original and received



(a) Satellite Map for the Range Testing

(b) Original Image

(c) Received Image

Fig. 3. Line-of-sight range testing.

images, respectively, at the boundary point. Although visible minor distortions appear in the received image, the image file is intact and readable, having the same size as the original.

The test results reveal an effective line-of-sight transmission range of 2143 m. Compared to existing WMSN studies using Zigbee, Xbee, or WiFi with typical transmission ranges of 100 m in outdoor settings, the proposed system is distinctly more suitable in deployment for larger scale dimensions.

3.2. RF serial and transmission rates

The RF transceiver has an adjustable serial port rate and RF rate. The default serial port and RF baud rates are both 9600. Seven serial port baud rates are possible: 1200, 2400, 4800, 9600, 19200, 38400, and 57600. Four exist for the RF baud rate: 2400, 4800, 9600, and 19200. During the initial range testing, the serial port and RF rates were both set to the highest values (i.e., serial port baud rate 57600, RF baud rate 19200), based on the hypothesis that these will deliver the maximum data rate. Indoor experiments were conducted to test the network data rate based on various configurations of these two parameters. Fig. 4 shows the test results validating the hypothesis.

As explained in Ref. [10], the average serial port rate must be lower than 55% of the RF rate, and both the serial port baud rate of 57600 bps and RF rate of 19200 bps comply with this requirement. The designed frame for image transmission was set to 242 bytes (240 bytes data payload and 2 bytes of framing information), whereas time slots had to be added between frames to avoid data overflow when sending images. The required time to send 242 bytes at baud rate 57600 is 242*10/57600 = 42 ms. Hence, the time slot required between frames is equal to (42/55%)*(57600/19200) − 42 = 187 ms. Thus, the transmission time for each image frame was 187 + 42 = 229 ms. The JPEG image file captured by the sensor station was approximately 12 KB, which could be divided into 12*1000/240 = 50 frames. Thus, the total transmission time for an image file was 50*229 = 11,450 ms, which yields an average data rate of 12*1000/11.45 = 1048 bytes/s. The field range testing described previously validates this calculation.

3.3. Power consumption

Battery usage is a crucial performance parameter in sensor networks and one of the major indicators of network energy efficiency and effective system design. Fig. 5 shows the live power consumption of the prototype node under three states: idle, when receiving data, and when transmitting data. The average power usage of the three states were also

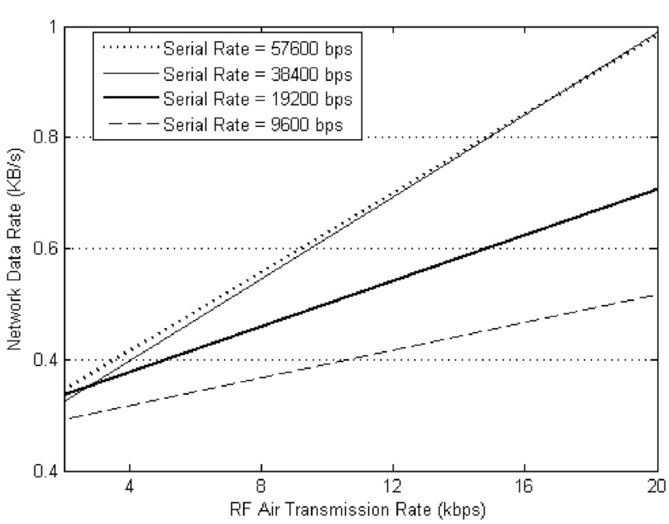


Fig. 4. Data rates of RF module.

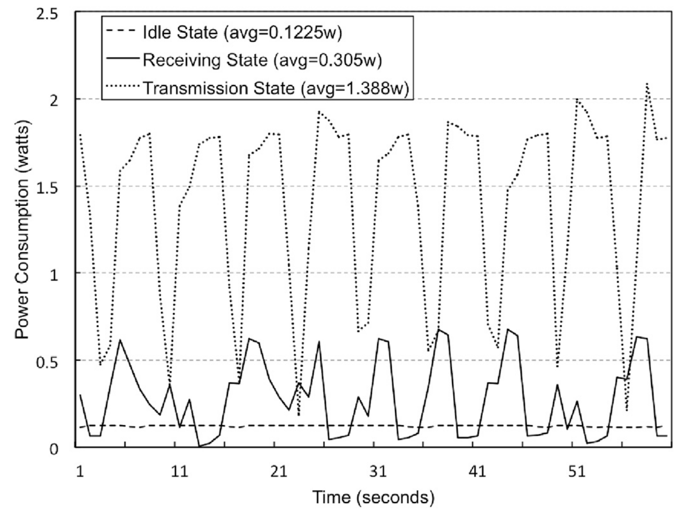
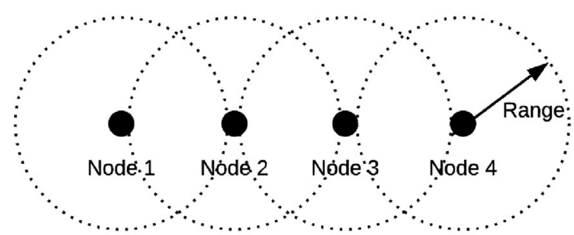


Fig. 5. Power consumption measurement.

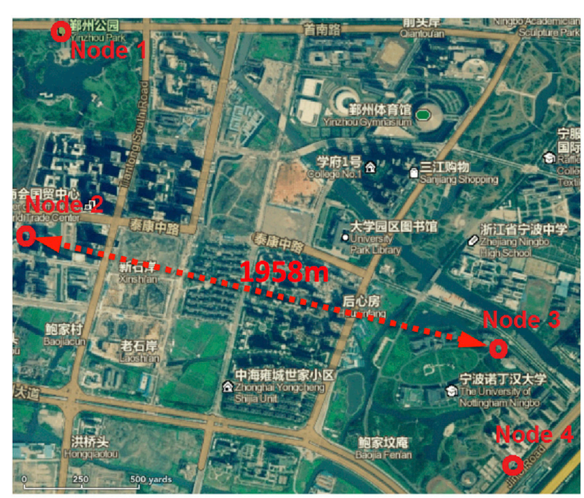
calculated. Using a pair of AA alkaline batteries with a total energy of 7.8 Wh, this system operated continuously for approximately 5 h in the transmission state, 25 h in the receiving state, and 63 h when idle. A considerably higher operational period could thus be easily obtained by increasing the quantity or type of batteries used. Therefore, this offers great prospects for feasible deployment in practical scenarios.

4. Network testing

A small-scale WSN was designed with a fixed topology as shown in Fig. 6(a). The fundamental purpose of this sensor network was to capture live images in various locations and transmit them to the final destination



(a) Logical Network Structure



(b) Satellite Map for the Practical Deployment

Fig. 6. Network scenario for the field test.

via the network. As in most other WSNs, this network scenario followed multiple sources and single destination traffic patterns. Four nodes were used in total, where Node 4 functioned as the sink node in which all received images were stored locally for further processing. The distance between every two adjacent sensor nodes had to be set to the effective transmission range, which meant that any nodes beyond the next-hop radius did not receive any data from the source node transmission.

The setup of the field-testing network was conducted through several outdoor experiments. To comply with the logical design shown in Fig. 6(a), four spots had to be identified by range-testing so that communication would not go beyond the next hop. Although the line-of-sight transmission range had shown a radius of more than 2000 m, practical deployment had to consider obstacles in the area such as buildings and trees, which cause RF signals to attenuate. The diversity of terrain attributes led to various transmission ranges in the practical scenario. For instance, the direct distance between Nodes 2 and 3 was much longer than that between others. After further investigation, four local positions were chosen as the testing spots, as shown in the satellite map of Fig. 6(b).

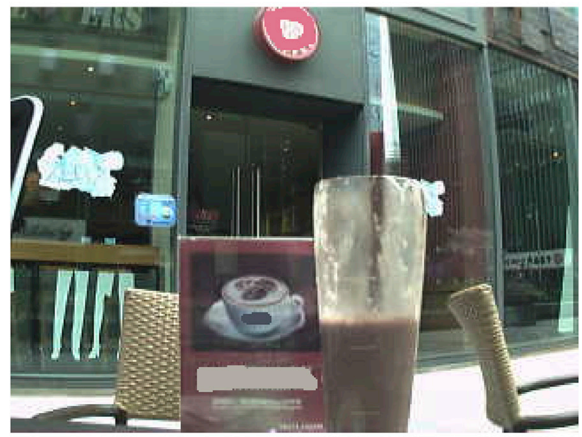
Networking protocol plays a vital role in saving power and providing consistent connections in wireless sensor communication. Several issues must be addressed prior to network protocol design, including low data rates, half-duplex communication patterns, and the possible contention of resources during the burst transmission period. Network characteristics have led to the use of a variation of time division multiplexing access (TDMA) [14] as the control protocol, as this can resolve the aforementioned problems. Each end sensor node is allocated with a time slot, during which it can transmit a captured image to the sink. Initially, a static routing mechanism is enabled for the data forwarding process, which is easy to implement in small-scale networks. This is based on the assumption that no acknowledgement packets are facilitated during the process of communication. Some advantages exist for using TDMA as the control protocol. First, no collisions occur between any two transmissions, as the end-to-end data delivery process for each sensor node is completed within its own time slot. Second, TDMA fits the half-duplex transceiver mechanism. The active sensor nodes are in either transmission- or receiving-only mode. Third, TDMA is used as a cross-layer control protocol, which is lightweight and efficient.

A simplified addressing scheme is used that operates in a similar manner to networkable protocol addressing schemes such as IP and IPX. The address identifies both the logical network location and physical address, which consequently leads to the use of a cross-layered design approach. One byte of information is reserved in the transmission frame for destination and source addresses, and a half byte is reserved for Time To Live (TTL). At the first stage of our research, only static routing was implemented to maintain the simplicity of the system. Each node address and piece of next hop information were determined in advance and embedded within each sensor's system. Within each time slot of data transmission, data packets followed a pre-determined route to reach the sink. Dynamic routing is worth considering in future research for large-scale network deployments. Regardless of the routing technique, the end-to-end data transmission should be completed within the respective time slot of each sensor node.

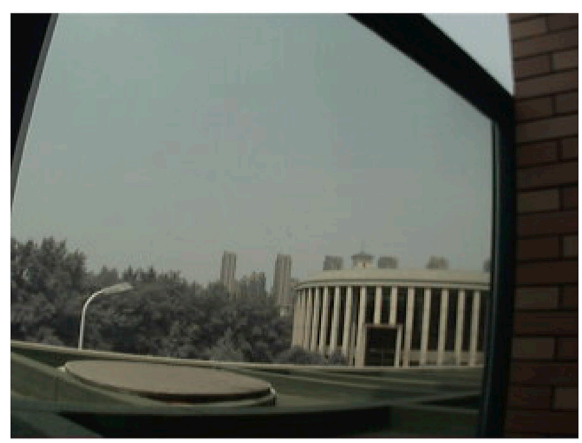
In the network scenario shown in Fig. 6, the maximum number of hops is 3, where a dead loop may occur during broadcasting communication. When Node 1 sends an image to the sink via Nodes 2 and 3, the image file may be broadcasted by Nodes 2 and 3, which then creates a dead loop. TTL is used to constrain the maximum number of hops each packet should go through in order to avoid dead loops.

Based on initial test results, the following optimal system parameters were used for further network testing. The RF serial port rate and air transmission rate were set to 57,600 and 19,200 bps, respectively. The buffer size was also set to the maximum, which is 256 bytes. Fig. 7(a)–(c) show the images received by the sink node that were captured by Nodes 1, 2, and 3, respectively. Node 1 captured an image of a driver inside a parked car, Node 2 of an image outside a coffee shop, and Node 3 of a balcony of a residential building. All received images were identical in quality to the originally transmitted files.

(a) Image Received from Node 1



(b) Image Received from Node 2



(c) Image Received from Node 3

Fig. 7. Images received by the sink in the field test.

5. Application scenarios

One issue with image sensing is that the camera must be adjusted to a certain angle to focus and capture desired images. In the case of traditional meter-reading sensors, such as temperature or pressure sensors, the sensing probes normally are flexible regarding orientation, regardless of the position of the whole sensor station. This means that these sensing probes may be deployed as a highly mobile network. However, a moving image sensor will be susceptible to focusing delay and the capturing angle. This confines wireless image sensor networks for deployment to relatively still topologies. Thus, their advantage over traditional surveillance networks is portability rather than mobility.

The relatively low data rate of the designed system makes it unsuitable for time-critical applications. However, the system should be effective in application scenarios that are delay-tolerant in the order of seconds. The RF modules used in this research have been tested for an effective line-of-sight transmission range of 2000 m for point-to-point communication, which demonstrates considerable potential for practical and expanded WMSN deployment. Despite the relatively low bandwidth of the designated RF module leading to a reduced data rate, the system remains suitable for certain practical scenarios. A wide range of applications exist to which the system can be tailored. These are summarized into three major categories as follows.

5.1. Surveillance networks

Most modern surveillance cameras are fixed on ceilings or the corners of buildings and are known as Closed-Circuit TeleVision (CCTV). This type of network has already matured and saturated the market. However, a gap exists in the market for temporary and ad-hoc surveillance systems. Our designed system can act as a convenient alternative to the permanent installation of CCTV cameras because of its low cost and portability. Surveillance application scenarios also include the monitoring of endangered animals, farms, and military compounds, as well as environmental monitoring and industrial process control, in which the potentials of the proposed system can be fully exploited.

5.2. Activity storage

The designed system can also be used for activity storage. For example, many Chinese cities have enforced a policy of installing a camera inside taxis for the purpose of recording illegal activities [15], as shown in Fig. 8. Despite the ongoing debate about the balance between security and privacy, this development demonstrates the need to archive image feeds in modern society. The system used in Chinese taxis is currently offline, and image or video data are gathered and processed at the end of each working day. If image sensor networks can participate in the activity storage process, collected image feeds can be received at the monitoring terminal in a live manner and be further processed for quicker response.

5.3. Robotic communication

Researchers in Refs. [16,17] tested WMSN for robotics applications using WiFi in which the activity scope was limited to indoor areas. The designated system has the advantage of long transmission ranges that are more suitable for outdoor scenarios. When a robot attempts to “tell” another robot what it “saw”, this is “information” and not “data” that is being relayed. Sending the entire image file for every communication can be cumbersome. Thus, delivering processed information would be more efficient. This research combined with that from studies on computer vision can lead to practical and more developed multidisciplinary research. For example, research in Ref. [18] enables computer vision in which the image frame size with extracted information is reduced to 30×30, producing a considerably reduced file size of 50 bytes (from an original size of 12 KB). With the current 1 KB/s data rate of the designed system, the communication delay between two robots is expected to be 50 ms, which qualifies for real-time communication (the acceptable delay for VoIP communication is 150 ms based on the ITU standard [19]).

Fig. 8. Camera enforced in Chinese taxies.

This category of application also includes family and health care scenarios in which only processed information must be delivered. The proposed system allows for remote monitoring for comparatively long-distance modes of implementation.

6. Conclusion and future work

This study investigated the feasibility and potential of using the ISM 433-MHz band to transmit data captured by image sensors. A hardware prototype was built using an effective line-of-sight transmission range of more than 2000 m. System testing for data rate and power consumption revealed the optimal configuration for system parameters and demonstrated the feasibility and effectiveness of the proposed system. A network of four multi-hop nodes was deployed in an outdoor location in which the quality of received images was the same as that of original images. Because the network delay was in the order of seconds, the designed network was deemed not suitable for time-critical applications. Three major categories of application scenarios were proposed that can take advantage of this type of image sensor network. Compared to existing surveillance networks, the benefit of a wireless image sensing network is portability rather than mobility. The findings in this study could be converted into knowledge transfer projects to stimulate greater input from industry for real-life applications. Future research directions may include the following topics.

6.1. Audio or video data transmission

At the initial research stage, only image transmission is experimented and tested. The current setting of a system yields a network delay in the order of seconds when delivering JPEG images, which means the designed network is unsuitable for time-critical applications and therefore may be challenging to stream continuous real-time audio or video signals. Should any specific application require audio information (e.g., audio fragments in a surveillance scenario), audio data can be compressed and transmitted separately or with the same time stamps as those of the image frames. The average file size of compressed audio content is 5 bits per sample [20], which is considerably negligible compared to the image frame captured by the system (e.g., average 12 KB). Thus, a pure audio-based application is definitely a viable option, whereas a combination of audio data and images should be subjected to future testing.

6.2. Robust control protocol

Future work might further investigate a robust control protocol for data communication. Although mobility is not currently an advantage of image sensing networks, these networks must have the ability of self-discovery, fault tolerance, and dynamic routing. This may represent a considerable challenge to the existing system, as the bandwidth and data rate are relatively limited.

6.3. Memory-based image compression

Regarding continuous image transmission, the network delay will become the bottleneck for network performance. A memory-based image compression algorithm can be adapted to reduce the transmitted file size. Each image can be regarded as an array of byte information. Between two adjacent image files, the identical pixel contents can be saved temporarily, and only different content must be transmitted. Researchers in Ref. [21] investigated a Wyner-Ziv video coding technique, which is worth adapting to this application.

6.4. Network informatics

Incorporating computer vision algorithms, a network system will need to send only processed information rather than original image data. Thus, network performance (especially latency) can be largely enhanced. A vast quantity of existing research has been conducted in the area of computer vision, of which image sensor networks can take advantage.

6.5. Hardware upgrade

Both computer vision and image compression require a relatively high performance microcontroller. Examining how Arduino can cope with these types of intensive calculations would be interesting. Other development systems can also be considered. For example, the STM32 development board is based on ARM and can offer high performance while maintaining low-power consumption. The system can also combine with a mechatronic motor to facilitate image capture from different angles.

6.6. Monitoring terminal

Future research can develop additional end-processing software to enable received images to be displayed live on a monitor. The current system stores all received images in an SD card within the sink node. Images presented live on a monitoring terminal from the user's perspective would be considerably more user-friendly.

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