World Academy of Science, Engineering and Technology
International Journal of Information and Communication Engineering
Vol:10, No:1, 2016

Design and Implementation of Active Radio Frequency Identification on Wireless Sensor Network-Based System

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Open Science Index, Information and Communication Engineering Vol:10, No:1, 2016 publications.waset.org/10003427.pdf

***Abstract*—**Wireless sensors, also known as wireless sensor nodes, have been making a significant impact on human daily life. The Radio Frequency Identification (RFID) and Wireless Sensor Network (WSN) are two complementary technologies; hence, an integrated implementation of these technologies expands the overall functionality in obtaining long-range and real-time information on the location and properties of objects and people. An approach for integrating ZigBee and RFID networks is proposed in this paper, to create an energy-efficient network improved by the benefits of combining ZigBee and RFID architecture. Furthermore, the compatibility and requirements of the ZigBee device and communication links in the typical RFID system which is presented with the real world experiment on the capabilities of the proposed RFID system.

***Keywords*—**Mesh network, RFID, wireless sensor network, zigbee.

I. INTRODUCTION

RADIO FREQUENCY IDENTIFICATION (RFID) is an automatic identification system that stores and remotely retrieves data from devices called RFID tags or transponders by using an interrogator (or reader) and a computer network [1]. The emerging technology of RFID promises to be a more comprehensive approach to data collection, and one of its potential applications is the improvement of supply-chain operations, offering a more automated and informative alternative to barcode. More recently, the evident benefits of an RFID system over barcode systems have formed a preference for RFID in the retail industry. These benefits give increased automation because of the ability of RFID tags to be read without a visual line-of-sight, as well as their ability to accumulate more information than barcodes. Additionally, due to the suitability of RFID technology in locating and tracking objects, RFID has been recently applied to many location identification systems to detect the presence of tagged objects and people. An RFID reader monitors the system, which is important in providing better and more efficient context-awareness services [2]. Furthermore, because reliable, sufficiently small, and adequately low cost RFID tags can now be built, the reputation of RFIDs has lately been on the demand. Recent advances in wireless communication, processing capability, and memory technology have fueled increasing research and industrial activity on the subject of Wireless Sensor Networks (WSN). WSN is a collection of a number of low-power, low-cost, multipurpose sensor nodes communicating wirelessly over a short distance [3]. Wireless sensors enable the technology for emerging cyber-physical systems, which will improve the quality of life [4]. This extended coverage and effectively improved reliability can dramatically improve the performance of an RFID system. Since WSN operates with low power consumption and low complexity, and since path signal loss is inversely related to range or distance, WSN-based RFID devices can operate in a wider area, and can function by multi-hop to reduce the requirement for long range transmission [5]. In view of the above, there is a need for essential research on protocols and algorithms that can improve RFID-based WSN performance and there by significantly benefit the emerging identification and monitoring applications.

II. PROPOSED SYSTEM DESIGN

In order to implement the communication reliability and energy efficiency in RFID system, a smart design is proposed for the RFID WSN-based system, which will utilize the modified algorithms. This new structure employs IEEE 802.15.4 protocol in tags and reader layers. The different tools that are available for implementation will be explored here, which inculcates the design and execution of the communication algorithm, using the ZigBee standard. The advantages of using a standard design incorporate the variety of applications, nodes, and test equipment that are available. The structure block diagram of an active RFID system and ZigBee technology integrates for intelligent identification and asset tracking systems which is shown in Fig. 1. The proposed RFID system addresses four major considerations, with their related attributes and goals:

1) Data circulation process and per-hop latency between tag and portable reader in multi-hop RFID based IEEE802.15.4.
2) Faster recognition of multiple tags to achieve high throughput, which can be subdivided as:
- Controlling tag packet transmission via overhead.
- Optimizing recognition of multiple RFID tags in the portable reader range.

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- Energy efficiency, which is a central challenge in designing RFID sensor nodes.
- Data circulation process and per-hop latency between portable reader and work station in multi-hop RFID based IEEE802.15.4.
- Attainment of a long communication range to connect with tags from one side and with the work station from the other side.

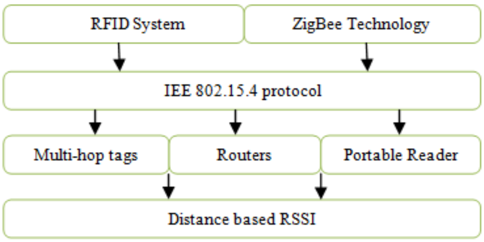

Fig. 1 Structure block diagram of system implementation

III. PROPOSED ACTIVE RFID TAGS

Due to its function, the tag has a simpler design compared to the reader. The long life battery-operated active RFID tag is designed to communicate with any active RFID reader in the vicinity, and thus the method of storing and retrieving data to the reader with high accuracy is a critical and crucial part of the tag design. Fig. 2 provides a block diagram that illustrates the PHY and the software layer of the proposed RFID tag. The PHY layer is composed of the ZigBee RF portion which is used for wireless communication. The microcontroller (MCU) portion is to be in charge of data computation and transmission operation, and function as a power source, as well as other associated hardware components. The RF transceiver architectural design is very similar to those used in the portable reader to enable the RFID tag to instantly detect a RSSI event. Thus, any addition to the signal pattern will immediately trigger the microcontroller to analyze the signal. Besides, the software layer, which is designed to meet the requirements of the RFID tag protocol that resides in the controller module, defines the functionality of the tag by receiving commands and transmitting data in two ways with the portable RFID reader by enabling a wireless transceiver communication between them.

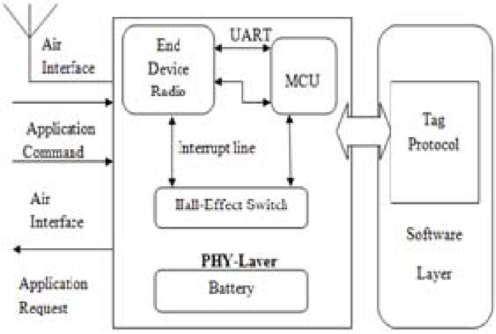

Fig. 2 The proposed RFID tag basic architecture

IV. DUTY-CYCLE MECHANISM FOR RFID TAGS

Since the low-duty-cycle mechanism is the default operation of the IEEE802.15.4 protocol the RFID tag algorithm in this work is originally designed using this mechanism in a multi-hop network. The mechanisms are as follow: before tags are registered to the reader system, during start-up and prior to integration with the environment system, all tag modules must enable low-duty-cycle operation in a multi-hop network. Then, the sensor nodes are put into sleep mode and triggered up periodically according to its schedule while waiting for an incoming broadcast frame from the RFID reader. If a tag needs to transmit, it must wait until the idle period is activated during the poll request time. However, if the feedback is null, tags are maintained in idle mode for most of the periods. Fig. 3 illustrates the implementation of the RFID tag duty cycle scheme.

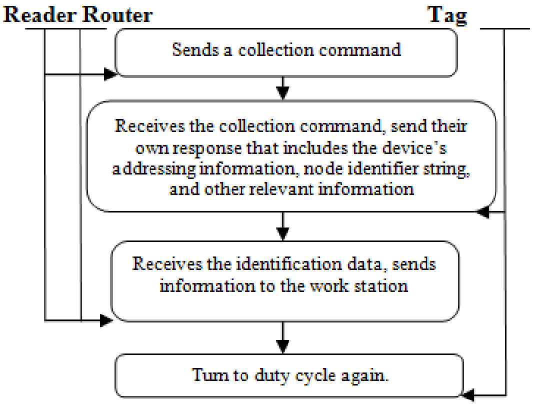

Fig. 3 Proposed duty cycle method of the RFID system

V. TRAVELING TIME DELAY FOR PROPOSED RFID SYSTEM

There are four kinds of traveling time delays:

1) Data traveling time in the air from the portable reader to the active tag (T_{RT}).
2) Data traveling time in the air from the active tag to the portable reader (T_{TR}).
3) Propagation delay at each hop (T_{PRO}).
4) Queuing delay at each hop (T_{QU}).

All the traveling time delays, T_{RT}, T_{TR}, T_{PROP} and T_{QU}, depend on the RFID node traffic, and also the distance between nodes. Let T_{TT} be the overall traveling time delay and $T_{RT} = T_{TR}$, thus,

$$T_{TT} = 2T_{RT} + T_{PRO} + T_{QU} \tag{1}$$

VI. TIME DELAY FORMULATION AND DETERMINES (READER TO/FROM TAGS)

The processing times $TP._{RTX}$ and T_{TTX} are the times before transmission in both the tag and portable reader that are required for the RF module to encode and transform the packet message to electromagnetic waves. Meanwhile, the processing times T_{TRX} and $TP._{RRX}$ are the times after reception in both the tag and portable reader that are required for the RF module to transform and decode the message from electromagnetic waves to binary data. The access time TCCA is the less inevitable part of packet delivery in WSN, varying from milliseconds up to seconds depending on the traffic load [4]. Constant time is always permanent and cannot be altered for the same type of the microcontroller (MCU). Even though, semi-constant time affects generally time complication which can be different even in same family of MCU, such as when the MCU execute two interrupts at the same time. Processing time inside the MCU such as interrupt handling and decoding are differences for the transmission and reception. Processing time for each instruction takes some time of the machine cycle delay to execute, machines cycle depending on controller type and crystal frequency, for 11.0592 MHz crystal, the time to execute one machine cycle is [6]:

$$11.0592\,\text{MHz}/12 = 921.6\,\text{KHz} \tag{2}$$

$$\text{T} = 1/921.6\,\text{K} = 1.085\,\mu\text{s} \tag{3}$$

Furthermore, in addition to the delays between instructions, all the instructions themselves require different amounts of time to execute. The traveling time parameter, a major parameter represents a key task in the RFID architecture design. It must be adjusted according to the distance between the portable reader and tag. Data travelling time in the air from the portable reader to active tag (T_{RT}), and vice versa (T_{TR}), can be calculated based on the time-distance relationship,

$$\text{Time} = \text{distance} \;/\; \text{RF velocity} \tag{4}$$

For example, suppose the distance between two nodes in the RFID network is 32 m, and the RF wave is (3 x 10^8) m/s; therefore, $T_{TR} = T_{RT}$, and one hop will take 0.000106667 ms. Moreover, the propagation delay (T_{PRO}) depends only on the distance between the two nodes, and the time value is below one microsecond for ranges under 300 meters [7]. The overall time function is differentiated by constant, semi-constant and traveling time parameters. Let T_{OVR_T} be the overall time incurred by each round-trip transaction of portable reader to tag and the reverse communication process, when all tags are responding; thus,

$$\text{Overall Time} = \text{Constant Time} + \text{Semi-Constant Time} + \text{Traveling Time} \tag{5}$$

$$T_{OVR\ T} = T_{C} + T_{SC} + {}_{TT} \tag{6}$$

$$\begin{aligned} T_{OVR\ T} &= TP._{RTX} + T_{TTX} + T_{TRX} + TP._{RRX} + \\ &T_{Boff} + T_{CCA} + T_{SCI} + T_{SC2} + 2T_{RT} + T_{PRO} + T_{OU} \end{aligned} \tag{7}$$

$$TOVR\_T = \sum\nolimits_{n}^{6} Tcn + \sum\nolimits_{n}^{2} Tsn + \sum\nolimits_{n}^{3} Ttn \tag{8}$$

Queuing delay (T_{QU}) becomes a dominant factor only in the case of heavy node traffic [8], [9], therefore there is no T_{QU}. Furthermore, in sensor networks, the propagation delay (TPRO) can be ignored because this time value is very low [10], [11]. Also, semi-constant time parameters are of secondary interest and are not taken into account in the RFID-based IEEE802.15.4 modeling time. Finally, all the constant parameters including the processing time delay and transmission delay are taken into account as in (9):

$$\begin{aligned} TOVR\_T &= TP._{RTX} + T_{TRX} + T_{TTX} + TP._{RRX} \\ &+ T_{Boff} + T_{CCA} + 2_{TRT} \end{aligned} \tag{9}$$

Since sending one byte over the radio in 250 Kbps takes 32 µs, sending the command frame to the portable reader will take 0.32 ms, and this is $TP._{RTX}$; meanwhile sending the packet according to the MAC data form will take 1.056 ms, which is T_{TTX}.

VII. Overall System Operations

Fig. 4 provides a block diagram that illustrates the main components of the proposed RFID system. The PHY encompasses the hardware platform that comprises a RFID reader portion represented by the RFID radio block and the end device radio block. The portable reader can be configured to operate in either the end device mode of operation or the RFID reader mode of operation. Alternatively, the portable RFID reader can also be configured to be operated in both modes concurrently to enable the continuous reception of transmission frames from a plurality of RFID tags.

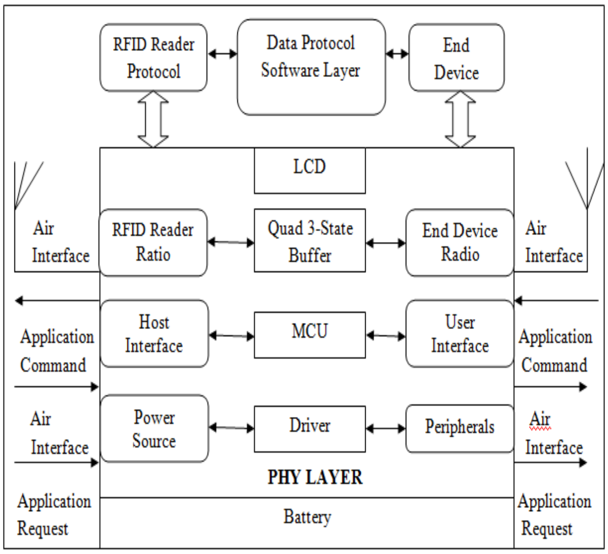

Fig. 4 Overall RFID system block diagram

The PHY layer provides the physical interface between the portable reader and the plurality of RFID tags via the RFID reader portion, and the physical interface between the portable reader and the remote work station via the end device portion. The end device portion of the portable reader is configured to support bidirectional wireless data communications to and from a remote work station via wireless transceivers. Similarly, the RFID reader portion is configured to support bidirectional data communication to and from a plurality of RFID tags that are deployed in the exemplary deployment environment via wireless transceivers. The software layer includes hardware layer dependent look-up tables that reside on the hardware level in an exemplary architecture of the portable RFID reader and are thus used to define the functionality of the portable reader. The software layer provides many of the functions associated with the plurality of RFID tags, such as making calls to functions and receiving commands from the work station.

VIII. RESULTS AND DISCUSSION

This section discusses the experimental results acquired from both the working prototypes and the modeled implementation over wireless mesh networks which can be described as the following:

1) First is the step to validate the models and the functionality of the proposed 2.4 GHz active RFID system implemented with the firmware and software where an environmental monitoring application is built, which demonstrated an execution matching for model characterizations.
2) Secondly is on the performance evaluation of the proposed system where several metrics are selected to reveal the fundamental tradeoffs in terms of the overall energy efficiency, latency in the aspect of end-to-end delay of a packet, and throughput in the aspect of tag collection time.
3) Lastly, to serve as a demonstration of the feasibility of the system. In fact, different tests are executed and analyzed according to various configuration parameters and a wide range of network conditions, such as the size of the network, density (number of tags), topology relationship, data traffic load, and total number of nodes.

All the testing is performed in the status quo environment. The test bed consists of 24 prototypes of RFID tags. One of the prototype of portable RFID reader, 10 routers, and a computer host.

A. Identifying the Tags and End – to – End Delay Latency Evaluation

Since quick collection time and data transfer ability are critical for delivering a large number of identification reports in a short time frame. This section explores the tag identification performance and end-to-end delay tradeoff latency of the existing typical RFID system and proposed RFID systems, through tests involving a packet moving through a multi-hop network. The main aim is to measure tag identification latency and quantify the benefits of the sleep mechanism, the environmental monitoring application which show how its performance matches the proposed model predictions which is further described below.

The whole network existed in mesh topology of 4-hops, and Fig. 5 corresponds to the deployment of the network components. The nodes automatically configure themselves into Tree in Mesh-based network [12]. The ZigBee Coordinator may be called the *parent* and the six ZigBee routers, as *children*. Moreover, each of these ZigBee Routers can also behave as a *parent* and in turn have a maximum of six ZigBee End Devices. Mesh topology is employed, as the ZigBee router of the portable reader may have to communicate with the farthest ZigBee router, which may be placed outside the permitted distances of the ZigBee router. Mesh topology permits data packets to pass through multiple hops in a network to route data from any source in any direction in different average traffic loads. In the current application, the portable reader communicated with any other ZigBee router in the network and vice versa.

A maximum distance of 17 m is maintained between any two routers, such that if a ZigBee router at a corridor is removed for some reason, and a new path could be established to route data packets automatically. Furthermore, the RF output power of the modules is reduced to minimum.

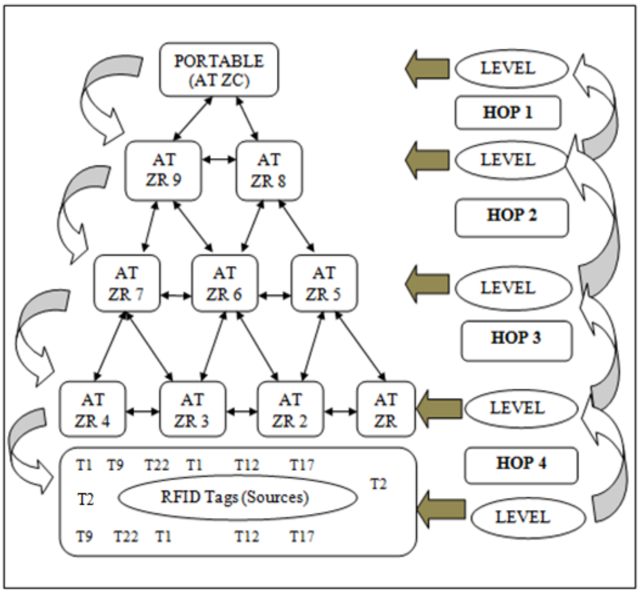

Fig. 5 Wireless mesh sensor network (RFID tags-portable reader) in multi- hop environment

The result demonstrates the reduction in tag identification latency when using the modified mechanism. The tag collection tests are conducted using two groups; one group periodically identify only one tag, the other group collect various numbers of tags at the same time. In order to periodically identify tags, the following assumptions are:

1) Only tag identification reports received at each round trip are taken into account.
2) Packets in the existing RFID system are each of 33 bytes long (PPDU), while packets in the developed RFID system (PPDU) systems are each of 20 bytes long. There is no fragmentation of any messages.
3) Within the 4-hop mesh topology network, at any specific time, one ZigBee router may have dramatically more data to send or receive than another ZigBee router.
4) The tags are configured to send in the lowest possible transmission power.

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5) When the tag packet has completed its round trip, the difference between the current timers' value and the initial value gives the round trip delay. The MCU's timer event may schedule this task, and
6) The latency delay per hop is then calculated by [13]:

$$\text{Latency delay} = \text{round trip} / \text{number of hops} \qquad (10)$$

1. Rudimentary Tag Tracking

First, the basic tag collection performance of the reader in the presence of only one tag is measured, using the standard *IEEE802.15.4* collection command defined in ZigBee protocol; the existing tag must respond to a discover command from the reader as soon as possible. In this assessment, a collection command time interval is generated in the portable reader and queued every 0.5 s, 0.6 s, 0.7 s and 0.8 s. The number of identifying messages is taken many times [14] and limited to be 500 packets to maintain validity and reliability for low and high traffic load. Table I summarizes the results with one tag; the traffic load is heavy when the time interval between messages is less than 700 ms. On the hand of the low traffic load, with an 800 ms arrival time, the tag is fully transported by the portable reader. While in the developed RFID system, the tag initiated the round trip by sending its identification data report (without listening for the reader command), received the ACK, and then returned to numb mode. An identification message is generated by the tag every 5 s, and then the round trip time of the packet is measured.

TABLE I
TAG COLLECTION TIME FOR EXISTING RFID SYSTEM

Time interval between messages ms	No. of sent collected command	No. of receive message	No. of missing message	% successfully read message
800	500	500	0	100
700	500	474	22	95.4
600	500	424	72	85.4
500	500	48	87	82.2

The round trip is repeated 500 times. The second packet of the second round trip is generated by the tag after the first one is received by the portable reader. The tag is fully identified by the portable reader in the developed RFID system within a 125 ms time arrival (round trip delay).

While in the proposed RFID system, the tag initiated the round trip by sending its identification data report (without listening for the reader command) while receiving the ACK, and then returned to numb mode. An identification message is generated by the tag every 5 s, and then the round trip time of the packet is measured. The round trip is repeated 500 times. The second packet of the second round trip is generated by the tag after the first one is received by the portable reader. The tag is located by the portable reader in the RFID system within a 125 ms time arrival (round trip delay). Fig. 6 demonstrates the average packet reduction in latency achieved for the proposed RFID compared to the typical RFID protocol, with 4-hop length and lowest network density.

In the proposed modified mechanism, tag identification packet latency is measured from the time the packet is generated by the tag to when it is sent to the portable reader. The RFID tag's extended packet of relative information is truncated when the tag wakes up. Even though this method provides considerable energy savings, it also reduces per-hop latency.

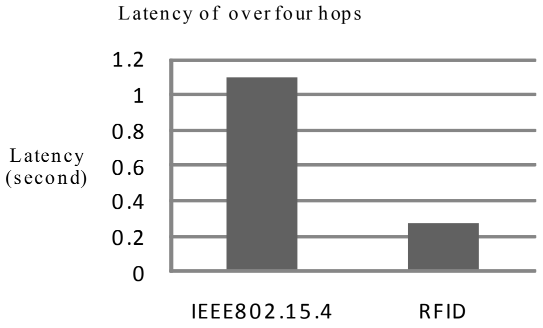

Fig. 6 Latency measurement over four hops

As a result, there is less failure in packet reception, due to the sleep mechanism that allows tags to go into idle mode only during the contention period when they are they required to send the packet. In contrast to the *IEEE 802.15.4 system*, tag identification packet latency is measured from the time the packet is generated by the portable reader to when the reader sends the data command to the tag. The MCU and radio listening energy components in the *IEEE 802.15.4 system* are crucial to the total energy consumption. The radio is listening idly for a long time and the MCU is always on during the idle period. This causes energy wastage and increases the per-hop latency. Furthermore, the long packet of the *IEEE 802.15.4* tag with its extra information increases the transmission overhead and thus increases latency. Moreover, when the standard protocol radio is offline according to its duty-cycle, it is unable to receive any data. It can only receive data when it is awake and polls its parent for data, at particular time it will respond to any message in the order in which they are received. Also from the results, the end-to-end delay latency increases proportionally with the number of hops, but the rates of increase are different for the two protocols spatially in the existing RFID system, since the fact that some messages at the tags (source nodes) may queued until finish the sleep cycles and enter active period. Furthermore, the tag in proposed RFID system need to wake up first from sleep mode then process and transmit its identification report, while the ZigBee routers does not consumes power for sleeping. As a result time is not wasted for wake up because there is no need to wait until the receiver router wakes up from the previous hop. For the existing RFID protocol, the end to end delay latency time (roundtrip) is nearly 1.1 s in multi-hop. Therefore, the packet incurs an average delay of 275 ms at each hop according to equation (11). In contrast, RFID experiences end delay latency time (round trip) closer to the average of 68.75 ms only. The result show that, the overall proposed RFID system latency is about 75% lower than for existing RFID system.

When traffic load is low, the network contention is reduced by maximizing the time to send identification data reports. Hence, a small amount of queuing delay is caused by the periodic sleep for each of the existing standard RFID tags. The results also show that when the portable reader in the existing standard RFID system detected the packets in a dense environment, it consumed a larger amount of processing time than is necessary to recognize only the identifier string. This is due to the extra information sent before the identifier string when network density and processing time in proportion increases (tags). For example, for the existing standard RFID system, for a particular tag case, there is one packet being sent every 0.8 s, while in the case of 5 tags there are 5 packets being sent every 3 s.

During high traffic load for the existing standard RFID *system*, contention occurs at each hop due to an increase in collisions, since the number of transmissions rises, which in turn notably adds to the tag collecting time (latency). Furthermore, the queuing delay for tags differs from that of ZigBee routers, because when one packet report sent at each round, the last tag packet report will have to wait fully for 24 rounds due to 24 number of tags tested. Fig. 7 shows the tag collection time results of the proposed *RFID system* compared to the existing standard RFID system, with multiple tags, with assured 100 % packet delivery. In the case of the high density network, a significant decrease in time can be noted (55.6%). However, wake-up time from deep sleep does not vary greatly as network density increases. Furthermore, there is only a small amount of processing time needed by the portable reader to verify each tag identifier string, compared to the original protocol. Therefore, the proposed *RFID system* is able to reliably send and receive tag packet reports in a much more heavy traffic load than the existing standard RFID.

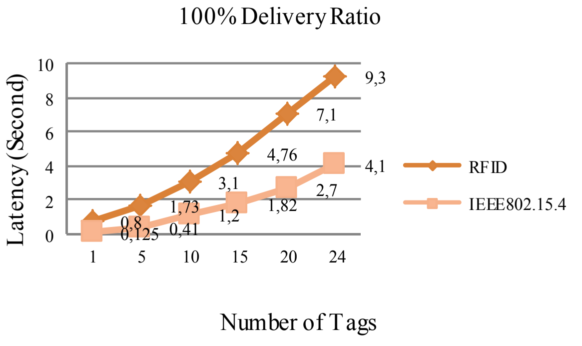

Fig. 7 Comparison of all tags collection

The comparison of end-to-end latency by using multi-hops with all the tags in the lowest network density is shown in Fig. 7, which illustrates that the rate of increase the collection time corresponding to the number of hops for the *RFID* is fairly lower than that of the standard. Again, the reason for this trend is that the sleep period during each tag cycle causes extra delay, and this extra delay increases as the density of the network increases. This happened when the number of tags increased. In this assessment, one packet is sent in each tag cycle, so the last packet (last tag) has to wait for at least 24 cycles.

IX. CONCLUSION

The results confirmed that the modified algorithm for proposed Radio Frequency Identification (RFID) system could yield reduced latency and tag collection time compared to the existing RFID system over *IEEE802.15.4*. The overall developed *RFID system* latency is about 60% lower than that for existing RFID system.

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