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A three-tier middleware architecture supporting bidirectional location tracking of numerous mobile nodes under legacy WSN environment

Dong-Kyu Lee, Tae-Hyon Kim, Seol-Young Jeong, Soon-Ju Kang *

College of IT, Kyungpook National University, 1370 Sangyuk-dong, Buk-gu, Daegu, Republic of Korea

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ABSTRACT

In the mobile asset management services applicable to warehouse, hospital, etc. a low-cost and practical bidirectional location tracking of mobile asset is one of the most important technical issue must be solved. Due to the complexity and heavy traffic of the legacy location-awareness techniques, simultaneous locationing and tracking of numerous mobile nodes in real-time is not easy. To address this problem, we propose the three-tier middleware architecture called uMATI (ubiquitous Mobile Asset Tracking Infra). In the uMATI, all nodes (stationary and mobile) commonly use the IEEE 802.15.4 MAC protocol to guarantee the compatibility with the legacy wireless sensor network (WSN) despite of mobile-stationary nodes co-existence network. To solve the bidirectional tracking in spite of the free mobility of the numerous mobile nodes, we firstly suggest a simple bidirectional location protocol called BLIDx (bidirectional location ID exchange) and its implementation into both the mobile and stationary nodes. In addition, to prevent the traffic overflow due to the concentration of excessive mobile nodes into a single location, we propose adding a specially designed stationary node called virtual sink (VS) node and installing related middleware components into the node. Results from the experimental evaluation prove that the proposed architecture enhanced the practicability by effectively supporting the mobility and managing the traffic in the real-time mobile asset tracking applications.

1. Introduction

This research regarding the wireless sensor network generally utilizes the conjoining of the stationary sensor nodes (stationary node) which collect the environmental sensor data in a fixed location and the mobile sensor nodes (mobile node) that travel around the sensing field, thereby forming the WSNs [1–5]. In these networks, the stationary nodes concurrently perform the two functions of obtaining the environmental data and acting as a location reference/communication proxy (access point) with numerous mobile nodes. The bidirectional mobile asset tracking service is one of the well-known applications of this network and is applicable to the settings such as warehouse, hospital, etc. [5–7]. However, the partial services are recently deployed only using the RFID-based one-way communication technique without free mobility [7] or the power-hungry WIFI tag [2,8] due to the difficulties in supporting the bidirectional communication and numerous mobile nodes. To pragmatically utilize the mobile asset tracking with full service, two issues should be solved urgently; firstly, the real-time reactivity in bidirectional localization and tracking should be implemented at the top of the legacy WSN protocol such as Zigbee [9–11] or 6LOWPAN [1], and secondly, the free-mobility support despite the large numbers of mobile nodes without loss of the bidirectional sensing and reporting capability of the legacy WSN [5,8,9].

However, most of the current location-aware techniques [1–4] are mostly focused on the precision of the location with the axis's of coordination including the excessive demand of stationary reference nodes despite of too much traffic. Much of those problems are caused the instability of the current WSN technology such as the frequent network reconfigurations for update the ad-hoc routing table due to the free-mobility of the mobile nodes [10–14]. In addition, a dense concentration of mobile nodes into a single location leads to the problems such as an increase in the traffic intensity, the congestion, and the high packet loss due to the inherent low bandwidth wireless communication channel of the WSN [14,15].

To address this problem, we propose the three-tier middleware architecture, called uMATI (ubiquitous Mobile Asset Tracking Infra) in which the stationary and mobile nodes co-exist and bidirectional communication among stationary and mobile nodes are fully supported. All core software component of uMATI was developed at the top of IEEE 802.15.4 MAC [18] which is the one of the most widely used industry-standard protocol in legacy WSN. The uMATI is composed of the three tiers: the mobility tier, the sensor network tier, and the backbone network tier. The mobility-tier

* Corresponding author. Tel.: +82 53 950 6604; fax: +82 53 950 5505.
E-mail addresses: edongq@ee.knu.ac.kr (D.-K. Lee), namestrike@ee.knu.ac.kr (T.-H. Kim), snowflower@ee.knu.ac.kr (S.-Y. Jeong), sjkang@ee.knu.ac.kr (S.-J. Kang).

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handles the communication between the stationary nodes and mobile nodes. In this tier, the stationary nodes act not only as the legacy sensor data handler, but also a location reference node with the function of the access point that communicate with numerous mobile nodes. For this purpose, BLIDx protocol is proposed to guarantee the efficient movement of mobile nodes in spite of supporting real-time tracking of numerous mobile nodes. The sensor network-tier functions as a traditional sensor network and only consists of the stationary nodes. In this tier, the mesh topology based ZigBee protocol [9] is used to support the multi-hop based ad-hoc communication. The backbone network-tier contains the traditional coordinator gateway (CG) for interfacing between PAN of sensor network and the backbone network, and additionally, the newly designed stationary nodes called virtual sink (VS) nodes that handle the traffic caused by the unexpected concentration of mobile nodes. The VS nodes act not only as a normal stationary node but also as a short cut sink node to reduce the traffic overload caused by a concentration of the mobile nodes. When the traffic increases, the VS node pumps the passerby data packets into the backbone network to decrease the traffic overload. Lastly, the uMATI thereby offers an effective bidirectional message delivery scheme defined according to the priority of the external event message and class of the message source nodes.

The contents of this paper are arranged in the following manner. Section 2 examines the domain description, motivation, and related researches related with uMATI. Section 3 explains the proposed uMATI architecture and the design factors that needed to be considered. Section 4 examines the detailed structure of the middleware components. Section 5 evaluates its performance and Section 6 gives the conclusion.

2. Domain descriptions and related work

2.1. Domain description

In order to help the understanding of the proposed concept in this paper, we introduce an example application service of uMATI, called mobile asset management service in warehouse management system [6,7] shown in Fig. 1. As shown in Fig. 1, a bidirectional mobile tag (mobile node) is attached in all of the managed mobile asset (boxes in Fig. 1), and in each unit space such as room or floor, a stationary node is attached to the ceiling. In order to give any message between nodes (both mobile and stationary), the all nodes (both mobile and stationary) have the bidirectional communication link. In this service, the mobile nodes that signal the respective locations and the internal conditions of the mobile asset (a box in Fig. 1), and a stationary node that collects the environmental data in a fixed position are conjoined to form a system. Additionally, the stationary node acts as a location reference node for the mobile nodes and also as an access point node to guarantee bidirectional communication between the mobile nodes and the other stationary nodes by exchanging the information regarding the locations of the mobile nodes.

Therefore, this warehouse management system collects the environmental data and controls it to maintain the optimal conditions to the stored or managed mobile asset items within the warehouse and identifies the location and tracking of each managed (or stored) item in parallel. Not only the locationing and tracking of the managed mobile asset, but the internal status change of the managed items such as exceptionally temperature change, open it abruptly, irregular vibration, etc. also be monitored and reported in real-time through the bidirectional communication channel between the mobile nodes and stationary nodes [6,7].

2.2. Survey of Indoor positioning and tracking techniques and availability in this domain

Extensive research has been done on localization for wireless networks. A general survey is found in [2–4]. Here, we provide a brief survey focusing only on localization techniques suitable for the multi-hop ad hoc WSN. The centralized localization techniques that are frequently deployed in the active RFID [4] or WIFI tag based solution [2,8] depend on the tag nodes transmitting data to a central location (RFID reader or WIFI access point devices), where computation is performed to determine the location of each tag node. Requiring central computation would be infeasible for mobile applications in WSN because of the high communication costs and inherent delay [2,3]. Due to this reason, generally the real-time locationing and tracking researches for WSN are focused on the distributed localization methods. Distributed localization methods do not centralize computation, and rely on each node determining its location with only limited communication with nearby nodes. These methods can be classified as "range-based" and "range-free". Range-based methods [2,3] use distance estimates such as signal strength (RSSI) or time of arrival (TDOA),

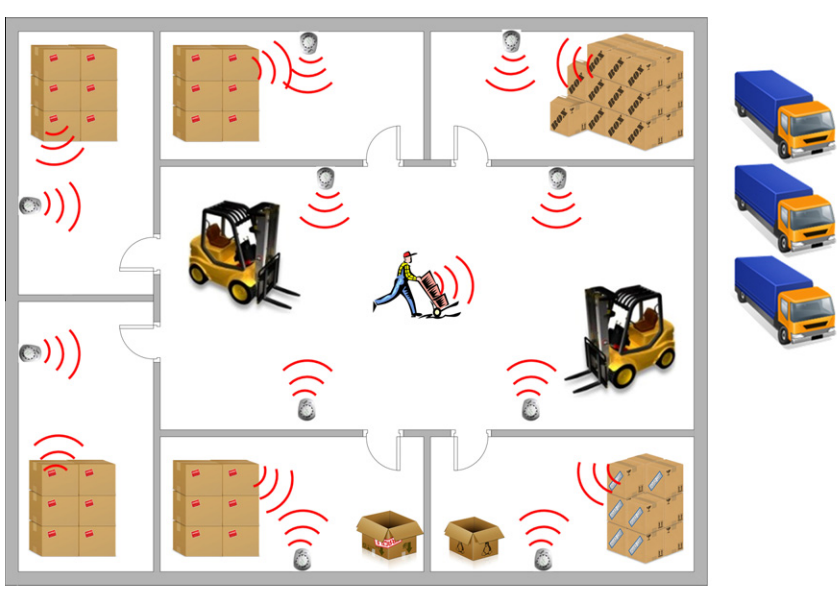

Fig. 1. Mobile asset management system which consists of the stationary and mobile nodes.

while a range-free solution depends only on the contents of messages received. The OPT (Online Person Tracking) system [16] is a typical example of the range-based approach which implements the well-known T-mote with IEEE 802.15.4 MAC. Based on the determined distance using RSSI, triangular location technique with weighted minimum mean square error (W-MMSE) location algorithm is suggested in OPT. Even though the OPT idea were referred by several recent researches and the commercial product such as TI's CC2431 [18], this idea lacks consideration regarding the real-time reactivity and fail to support numerous mobile nodes due to the high computing time. Regarding the range-free methods [20,21], two types of algorithms were proposed for WSN; multiple location reference nodes broadcast beaconing to every mobile nodes and hop counting method to estimate the location of the mobile nodes. In the hop counting approach [20], each mobile node maintains a counter denoting the minimum number of hops to each location reference node. Where the mobile nodes are widely spread and the density of the location reference nodes is low, this approach is possible to deploy. But, in the opposite cases the performance is too sensitive to increase the number of mobile nodes. Regarding the beaconing method by the reference nodes, the APIT method [19] isolates the environment into triangular regions between beaconing nodes, and uses a grid algorithm to calculate the maximum area in which a node will likely reside. MCL (Monte Carlo Localization) [21] was also proposed for mobile robot location tracking and mobile nodes localization. Despite the novelty of these methods, these are still too sensitive to guarantee the real-time reactivity (milli-second level) that involves hundreds or thousands mobile nodes are in act. Thus, the beaconing is simple but the back-end computation requires too much computing time.

2.3. Technical problems to be solved in the WSN-based approach

2.3.1. How one can maximize the reactivity identifying the location of mobile nodes in both server-side and mobile itself?

To solve the high constraints (milli-second level reactivity and thousands of mobile nodes) in this domain and the high back-end computing times in existing localization methods [2–5], we could not help re-designing a new indoor positioning method and implemented the Asy-IDx [22] protocol in our previous study. The Asy-IDx protocol separates the network layer and MAC layer because the routing problem of the network layer protocol made the existing protocol impossible to support the free mobility. In Ays-IDx, all stationary nodes act as the location reference node and communication proxy node for lots of mobile nodes. When mobile nodes are approaching to the RF coverage of a stationary node, a stationary node detects the existence of mobile nodes using additional sensors (e.g. motion sensor) in itself, then broadcasts beacon message with its ID to all mobile nodes. Each mobile node compares the current RSSI value from the stationary with the old one then if the value from new stationary is better, the mobile node change the communication proxy to the new stationary node which would mean that the locations changed (exchange each IDs both stationary and mobile, and the stationary send the IDs of mobiles to server-side and each mobiles recognize the ID of the stationary as its location). Using this simple Asy-IDx protocol, we could achieve the highest reactive performance (below than 50 ms) ever seen. Additionally, it was less sensitive with sudden rapid increasing the number of mobile nodes. Despite the excellent performance, we met lots of technical problems due to the incompleteness and impractical implementation of the early concept of Asy-IDx. The problems of the Asy-IDx are the basic motivation in this paper. We have tried to overcome the problems using two approaches; one is the newly practical design of the BLIDx explained in Section 4.1.2 in this paper. The other is the middleware design to solve the congestion problem describe in the following.

2.3.2. How to solve the problems supporting the numerous mobile nodes in real-time

In the proposed application domain, supporting the mobile nodes becomes especially severe when the frequency of the network reorganization increases due to the numerous mobile nodes randomly changing their locations. Industry-standard protocols such as Zigbee or 6LOWPAN support the realignment to build an association between neighboring sensor nodes. However, the excessive number of mobile nodes changing the respective positions frequently, causes the stationary node to fail to update its routing table properly with this abnormal orphan procedure [10–14]. The recovery mechanism of the legacy wireless sensor network protocol cannot support multiple instances of the node mobility. Therefore, the mobile nodes which failed to join the sensor network cannot send data regarding their environment and locations to the stationary nodes [17,23–26].

In addition, when the mobile nodes are densely concentrated on a single location, they may all attempt to connect to a single stationary node in the vicinity. However, considering the memory limits of the embedded sensor node, the stationary node may not be able to maintain the information associated with multiple mobile nodes, thus only few of them joining the network successfully. The mobile nodes which failed to join the network would repeat such attempts, thereby worsening the WSN contributions. Fig. 2 shows such an instance: increased communication harms the wireless sensor network with a low-bandwidth, creating a critical situation [28]. Some researchers have proposed to reduce the impact on legacy WSN that occurs during the association procedure between stationary and mobile nodes [15,27,28]. But these studies couldn't overcome the numerous mobile nodes with less relation with the number of access point nodes (stationary nodes). The other study groups have tried to use the multiple radio frequency channels or multiple communication protocols [29,30]. The stationary nodes communicate to other stationary nodes with general wireless sensor network protocol but they use an additional wireless communication protocol to communicate with mobile nodes. But, this architecture still suffers from certain critical flaws in that such will inevitably increase the manufacturing cost of sensor nodes and high power consumption due to the dual RF channel and/or chips. In addition, a number of other congestion control schemes have been proposed for sensor networks to address congestion of numerous mobile nodes in a single location. In general, congestion control schemes use various mechanisms for mitigating congestion through rate control and packet drop mechanisms [31–34]. When congestion occurs, such schemes provide the flow control necessary to drop some data that cannot be stored within memory space. The rate of this occurrence is restricted to ensure

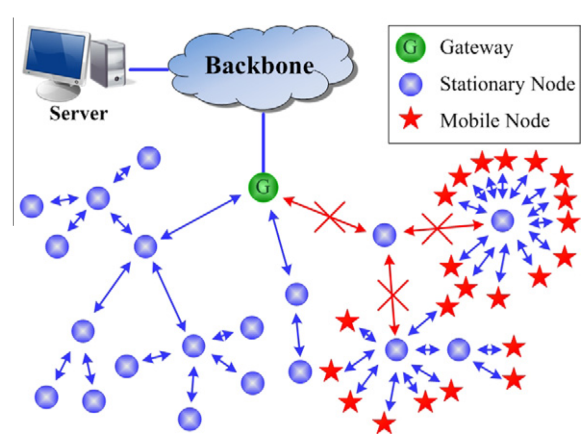

Fig. 2. Congestion problem according to the density concentration of mobile nodes.

unbiased priority data transmission by the sensor nodes [30]. Some congestion control schemes use new routing passage to transfer the data. When congestion occurs, sensor nodes detect the lower traffic status of neighbor nodes and redirect the traffic through the neighboring nodes [33,34]. Redirect passage architecture stores data in two passes: one is the original data passage occurring in a normal situation while the other is the new data passage occurring in a traffic overload situation. Therefore, redirect passage architecture occurs more than double network reconfiguration does which is caused by the movement of mobile nodes. Hence, these previous researches couldn't solve the dense concentration of mobile nodes at a single location associated with the frequent movement of mobile nodes.

3. Design consideration and conceptual design of proposed architecture

3.1. Design consideration

To solve the aforementioned problems, the proposed system must try to minimize the frequent network reconfiguration required to compensate for the random movement of mobile nodes, guarantee the flex mobility in spite of numerous number of mobile nodes, and solve the problem of increased traffic due to the dense concentration of mobile nodes. Therefore, the following design factors need to be considered when constructing wireless sensor networks.

Firstly, the impact of the traveling mobile nodes must be minimized while guaranteeing their free-mobility. Hence, an architecture that can guarantee the mobility of the mobile nodes while minimizing their impact on the pre-established network is essential.

Secondly, the congestion problem that occurs with excessive communication traffic due to the high-density concentration of mobile nodes must be addressed. When mobile nodes are concentrated, traffic overload occurs as a consequence of the communication traffic that is generated. This results in heightened competition between the mobile nodes to secure a communication channel with the sensor nodes. In congestion, stationary node communicate is likely to fail when uploading packets even if the stationary nodes successfully communicate with mobile nodes. This problem of data loss caused by congestion is especially severe in the case of nodes that are connected by multiple hops.

Thirdly, compatibility with current wireless sensor network protocols must be provided. The architecture, while guaranteeing the mobility of the mobile nodes and reducing excessive communication, must function as a single system in respect to cooperation. Cooperation with the pre-established standard sensor network protocol will allow the network to appear functioning as a single system while reducing the impact of the mobile nodes on the wireless sensor network.

Fourthly, location awareness must be provided between the stationary node and the mobile nodes. As they relocate, the mobile nodes transfer their location and sensing data to the stationary node that is in the best communicative condition. Simultaneously, the stationary node having the most optimal communication with the mobile nodes will change as the mobile nodes relocate. Consequently, the passage through which the mobile nodes transfer data to the server will change as well. In other words, the stationary nodes that communicate with the mobile nodes will change according to their communicative status. Therefore, in order to confirm data transfer to a mobile node, the stationary node that is capable of communicating with the mobile node must be identified.

Lastly, all the sensor nodes must have the same address scheme and homogeneous protocol. This will allow the control of the sensor node and general system maintenance to be more efficient. Since the stationary node uses the same physical and MAC layer as the mobile nodes, the system's uniformity and the manufacturing cost will be improved.

3.2. Conceptual design of the proposed architecture

Fig. 3 shows the proposed three-tier WSN architecture which consists of a mobility tier, sensor network tier, and backbone network tier. The mobility tier is composed of multiple mobile nodes, which communicate to stationary nodes using IEEE802.15.4 MAC communication. The sensor network tier is composed of multiple stationary nodes that transfer the mobile nodes' sensing and location data. Lastly, the backbone network tier that is connected to the server collects the sensing data received from the gateway node or the VS node for the server to process for the user.

The stationary nodes and the mobile nodes use homogenous physical and MAC protocol, and are only different in network layer protocol. Because mobile nodes do not have the network protocol stack, only stationary nodes use the network protocol stack. Therefore, the sensor network tier is solely composed of multiple stationary nodes that use the network protocol stack. The sensor

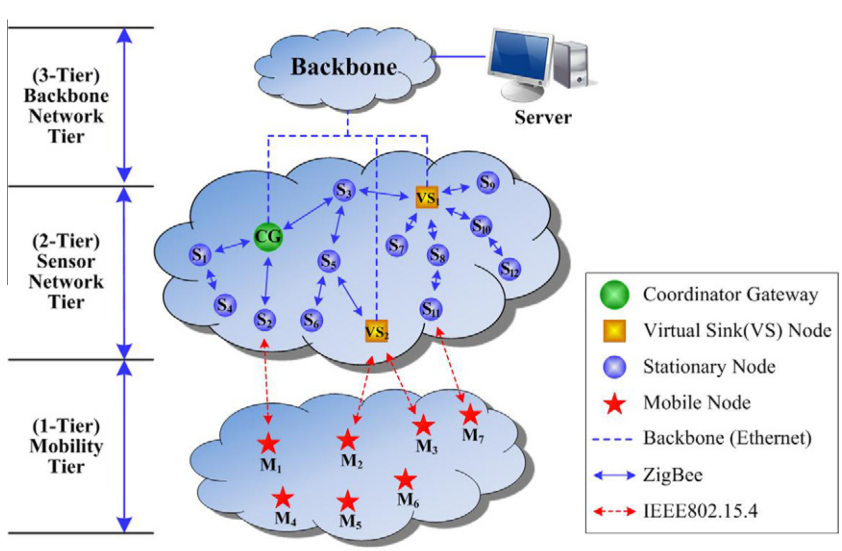

Fig. 3. Overview of the proposed the three-tiered uMATI architecture.

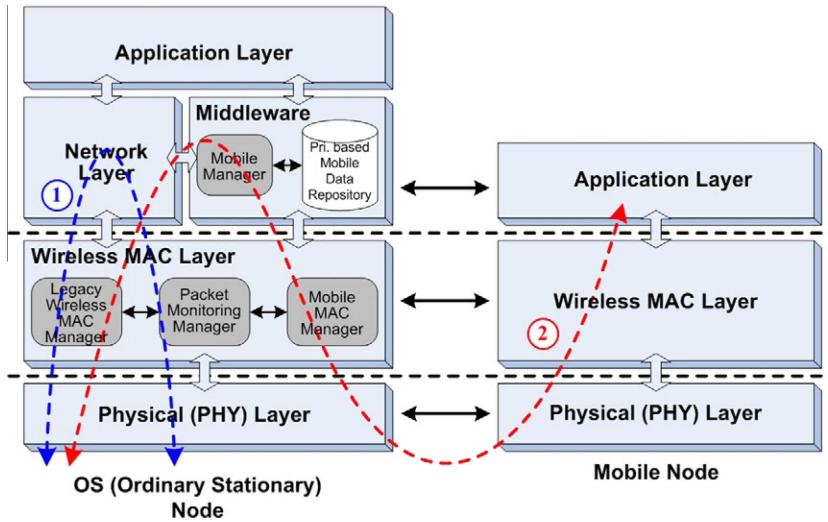

Fig. 4. uMATI components in OS node for communicating with mobile node.

network tier and the mobility tier are loosely-coupled using BLIDx protocol which is essential for assuring the sustainability of the basic service. Most of the problems are caused by the operating services in which the location-awareness service and basic sensor network service are on the same network protocol stack. Thus, dramatic advantages can be achieved by using the two loosely-couple tiers. In general, the frequent movement of numerous mobile nodes cause frequent network reconfiguration, but such a tendency can be reduced by using the proposed architecture. In the proposed architecture, the mobile nodes' movements do not impact sensor network reconfiguration because the mobile nodes do not use the network protocol; they only influence the condition of the physical network while holding a communication channel.

In addition, when multiple mobile nodes travel from one area to another, it is possible that they will become concentrated on a single location. The dense concentration of mobile nodes leads to the increased traffic intensity and congestion. To solve this problem, a VS node, a specially designed stationary node embedded with a wide bandwidth interface and used as an Ethernet, was added to the sensor network tier. The VS node joins the sensor network and functions in the same manner as the pre-established stationary node. When congestion occurs, the VS nodes pump the passerby data packets into the backbone network equipped with a wide bandwidth network. Hence, the general usage of a WSN's low bandwidth could be decreased, thereby improving the reliability of the wireless sensor network.

4. Detail design

4.1. Mobility tier (1-tier)

The mobility tier supports communication between the stationary nodes, mobile nodes, and the location-awareness service of the traveling mobile nodes. In this tier, the mobile nodes change their location freely while the stationary nodes act as an access point to communicate with mobile nodes.

4.1.1. Mobility support architecture

This paper proposes a mobility tier structure based on IEEE802.15.4 MAC that minimizes the potential disruption caused by traveling mobile nodes while maximizing fluent communication between mobile and stationary nodes.

Fig. 4 shows the uMATI components for ordinary stationary (use OS for differentiate with the VS) nodes and mobile nodes. The blue arrowed line[1] (marked ①) means the data flow for the traditional stationary sensor network application such as gathering environmental sensing data. All software components in blue line are the standard Zigbee and IEEE 802.15.4 MAC related. The red line (marked ②) is the data flow between mobile and stationary using the proposed BLIDx protocol and middleware in this paper. The component in the red line related with the two functions; one is the location reference identification and the other is the access point for the bidirectional communication link between mobile to stationary even though the priority based packet handling.

As the diagram reveals, both the mobile and OS nodes share the same physical and MAC layers, thereby providing the same communicative environment between the two. The mobile nodes do not contain a network layer. Therefore, they can only communicate with an OS node positioned within the range of radio frequency and are incapable of communication by multi-hopping.

The proposed architecture would reduce the impact on sensor network configuration by using the MAC communication exclusively as opposed to using the sensor network protocol. Although an increase in traffic while communicating with the stationary node would still occur, unlike the current wireless sensor network, the rise in traffic would not be drastic, permitting sensor node mobility and preventing a drop in the reliability of the sensor network. The arrowed line ① in Fig. 4 means the communication path between the legacy WSN protocol and the line ② shows the communication path between mobile node and stationary node.

4.1.2. Location awareness using BLIDx protocol

In order to clarify their respective locations, mobile nodes send their ID to the nearby stationary nodes, which in turn send the location information to the server. Then the server renews the information regarding the locations of the mobile nodes. Fig. 5 is the sequence diagram showing the ID exchange between mobile nodes and stationary nodes.

Initially, to send a mobile node location update to the server, the mobile node that has relocated must find the surrounding neighbor stationary node that has the best communicative condition by broadcasting the stationary node ID (SID) request packet

[1] For interpretation of color in Fig. 4, the reader is referred to the web version of this article.

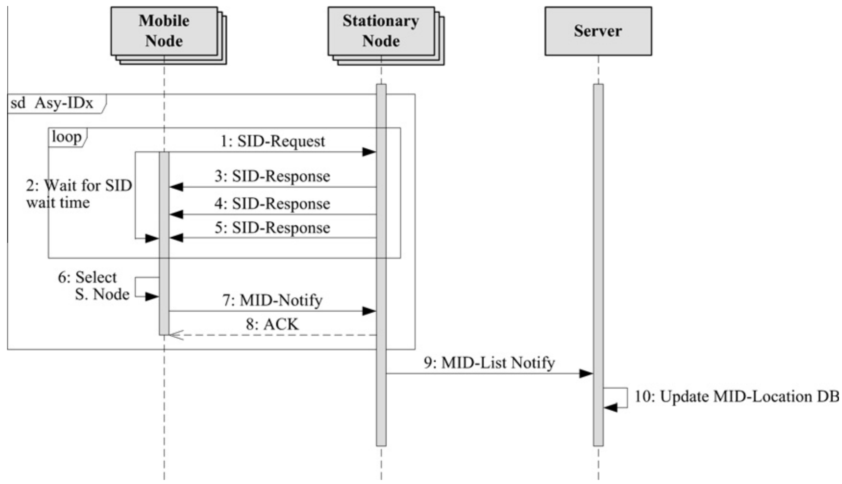

Fig. 5. Sequence diagram of BLIDx protocol and location updating sequence of mobile node.

(1) the mobile node waits for the SID Wait Time that is predefined, (2) the stationary nodes that receive the SID request packet send a response packet back at the constant interval several times to the mobile node along with their SID, (3–5) then, the mobile nodes select a stationary node as a location ID node (the best communication quality stationary node with the mobile node) and decide the stationary node as the node will interact with in further communication before the location of the mobile node be changed, (6) after that, to notify the selected stationary node of their respective locations, the mobile nodes will send them the Mobile node ID (MID), (7) the stationary node will respond to the mobile nodes, (8) passing the information to the server via sensor network (9) the server that receives the information from the stationary node will renew the location data of the mobile nodes, (10) after this procedure, using the stored location data of the mobile nodes, the server can provide the location awareness service or message transference service.

The BLIDx is an practically redesigned version of Asy-IDx (Asynchronous ID exchange) protocol in our previous study [22]. In order to guarantee the millisecond level reactivity in locationing and tracking, both Asy-IDx and BLIDx separate the network layer and MAC layer because the routing problem of the network layer made the existing protocol impossible to support the free mobility and performance. Therefore, two protocols similarly works as following: firstly, all stationary nodes act as the location reference node and communication proxy node for lots of mobile nodes, and secondly, when a pairing is successful between a mobile and a stationary, the both sides simultaneously exchange their IDs (IDx). The ID of stationary is the location information of itself to the mobile node and the IDs of mobile nodes are forwarded by the stationary to sever-side for location tracking service. The time in which the IDx occurs is the first difference between Asy-IDx and BLIDx. In the Asy-IDx [22], an additional sensor (motion sensor) installed in all stationary nodes detects any movement in the coverage area. If any movement detected then the motion sensor activates the stationary, and the stationary broadcasts beaconing with its ID. Due to this mechanism, if several mobile nodes simultaneously move around, too many stationary activated and too much IDx within meaningless short time range and multiple locations for a mobile occurred because the mobile does not consider the neighbor effect of the multiple stationary nodes. To prevent this symptom and remove the extra-ordinary sensors (motion sensors), in BLIDx, a mobile node requests any beaconing to neighbor stationary nodes only if required, then the listened neighbor stationary nodes react and periodically broadcast its beaconing with its ID. Within a limited time, each mobile node can accumulate the beaconing information from several stationary nodes and then decides the nearest stationary node (by comparing the quality of beaconing (e.g. RSSI)) as its location. Additionally, the mobile nodes compare the new ID with old one and if changed, then the mobile send the MID-Notify action (7) shown in Fig. 5 for reporting new location to server-side. These difference should be effected in the reactivity performance and the battery life-span of mobile nodes due to the frequent wake-up for accumulating the stationary beaconings but we can identify the negligible quantity of effect in the test-bed experiments as shown in Figs. 9 and 10b in this paper.

4.2. Sensor network tier (2-tier)

The sensor network tier is the same as a traditional sensor network that consists of only stationary nodes. Each stationary node obtains environmental data and transfers it to the gateway, as the nodes support routing the passerby data from others.

4.2.1. Legacy sensor network function

Sensor network is composed of enough stationary nodes to fully cover the sensing area. Each stationary nodes has the not only the sensing environmental data and but also ad-hoc routing (some of them) to send the data to destination nodes using the embedded protocol stack. The stationary nodes are equipped with sensors to get environmental data such as temperature, humidity, etc. The arrowed line labeled with ① in the Fig. 4 shows the process in which the data is transferred using multi-hop routing in the network layer that supports wireless sensor network protocol.

4.2.2. uMATI software architecture of OS node

Stationary nodes can communicate with numerous mobile nodes by operating not only as a location reference node but also as an access point node. The stationary nodes wrap the data from the mobile nodes up into the WSN protocol packet data.

The uMATI software architecture of a stationary node is shown in Fig. 4. The stationary node supports the physical layer, MAC layer, and network layer. The wireless MAC layer consists of a Legacy Wireless MAC Manager (LWM Manager), a Mobile MAC Manager (MM Manager), and a Packet Monitoring Manager (PM Manager). The LWM Manager supports the current sensor network protocol, serving as a connection between the MAC and network layer when data is transferred via the wireless sensor network. The MM Manager supports the mobile nodes and communication while sending the data received from the mobile node to the middleware instead of the network layer, allowing the middleware to process the data from the mobile node. The middleware consists of a Mobile Location Manager (ML Manager). The ML Manager supports location awareness of the mobile nodes using BLIDx procedure. The arrowed line ② in the Fig. 4 illustrates the instance where the mobile node and the stationary node communicate. The data received from the mobile node passes through the MM Manager in the wireless MAC layer and the application layer of the stationary node using wireless sensory network protocol. The same process occurs in the opposite case where the data received from the stationary node, in which stationary node is sent to the mobile node through the MM manager.

4.2.3. Common address scheme

Both mobile and stationary nodes possess a unique MAC address that can be used as the indicator of a unit location (e.g. room id, floor id, etc.). Also the MAC address assigned to the mobile node can be used as the unique ID for each mobile node. The locations of each stationary node are mapped with the corresponding geometric information. The server recognizes the locations of the mobile nodes which communicate to the stationary node by using BLIDx procedure. Hence, the physical location of the mobile nodes will be recognized by the reference of the stationary nodes.

In the proposed architecture, the mobile nodes only support one-hop communication unlike the stationary nodes, and does not use a standard network layer protocol [9] that has a multihop routing mechanism. The stationary nodes share the same physical and MAC layer along with the mobile nodes, which is much more advantageous than using a completely different communication stack. Because the stationary and mobile nodes share the same MAC communication the Mac layer is able to recognize this, although the two nodes use different protocols on the network layer. Also, sharing the same MAC-based communication prevents the overhead that results from channel switching and makes the use of an extra communication module unnecessary.

In legacy WSN, the stationary node receives new node IDs from the sensor network according to the network's structure, but because there is no network layer in the mobile node, communication using this information is not viable. Also, this requires address mapping for the address exchange in the address structures of the stationary and mobile nodes. However, this problem can be solved by using the MAC-based common address scheme. It reduces breakouts of the aforementioned problem when the mobile and stationary nodes are communicating to each other. Furthermore, using the same address scheme allows one message to be sent simultaneously to both the mobile and stationary node when the mobile node is trying to send multiple duplicate data to a stationary node and another mobile node. For instance, in the case of an emergency, the mobile node will be able to send an alarm to both a stationary and another mobile node at once.

4.2.4. Priority based packet delivery services

Due to the high frequency of BLIDx between a stationary node and numerous mobile nodes, the loss of data packet should be send is possible to occur when lots of mobile nodes are concentrated at a single location. In order to prevent this situation, the priority-based packet handling and delivery scheme was given uMATI architecture. In general cases, the periodic environmental sensing data is not time or safety critical, but some sporadically interrupted sensing data is the critical emergency event data should be sent it urgently.

All packets generated in uMATI have been classified with the 3 level priorities as shown in Table 1: high, medium, low. The high priority denotes an emergence situation or an emergency response packet. The medium priority denotes the location information of mobile nodes. A low priority packet denotes the periodic sensing data from both stationary and mobile nodes.

Table 1
Priority levels classified by packet types.

Source	Type	Priority	Description
Stationary node	Periodic sensing data	Low	Periodic sensing data as temperature, humidity, etc.
Stationary node	Emergence sensing data	High	Detect an intruder or detect a fire situation
Mobile node	Periodic sensing data	Low	Periodic sensing data as a temperature, motion, etc.
Mobile node	Location information	Medium	BLIDx of mobile nodes (36 bytes)
Mobile node	Emergence data	High	Emergence call for help

4.3. Backbone network tier (2-tier)

The backbone network tier consists of a server and stationary nodes which are connected to the backbone network as a gateway and some VS nodes.

4.3.1. Introduction of VS node

This paper proposes the VS node as a solution to the problem of traffic congestion due to the concentration of numerous mobile nodes in a single zone. The VS node supports both the wireless communication function with numerous mobile nodes and the wide bandwidth communication path to handle the traffic congestion effectively. The VS node pumps the passerby data to the backbone network which will be transferred to the server amidst the ongoing heavy traffic due to the high density concentration of the mobile nodes. Even if stationary nodes can successfully communicate with mobile nodes, the stationary nodes may fail to upload packets. The VS nodes can prevent the packet loss during a high density concentration of mobile nodes and stabilize the traffic balance in WSN in spite of the numerous mobile nodes. Fig. 6 shows the conceptual design of a VS node based on the wireless sensor network.

The VS node joins the network through the same process that the stationary node undergoes. When numerous mobile nodes are densely concentrated in a single area, the heavy traffic is inevitably occurred due to the frequent network reconfiguration and data transference requests from mobile nodes. Under such circumstances, the VS node checks the passing data and directly pumps the packets to the backbone network. The VS node transfers upstream data through the backbone network to the server, thereby reducing the traffic after the node itself. Using this principle, a reduction of the network instability problem associated with high traffic in a wireless sensor network with a low bandwidth can be realized. As shown in Fig. 6, they are four types of passages used in transferring data through the VS nodes. Firstly, label ① in the Fig. 6 shows the process in which the data is transferred from the sensor nodes to the server. The sensor nodes send the sensing data and the mobile nodes' location data to the server. If the data is destined to reach the server, the VS node pumps the data into the backbone network so that it will be transferred to the server. Secondly, label ② in Fig. 6 illustrates the passage that the sensor nodes use to the transfer configuration and management data to the coordinator node or parent nodes. Regarding the configuration and management data, the VS node sends it to the ancestor nodes or the coordinator node through the wireless sensor network. Thirdly, label ③ in Fig. 6 shows that the sensor nodes sends to the another sensor nodes. In this case, the VS node routes the data into the wireless sensor network without VS. Finally, label ④ in Fig. 6 shows the passage that the server uses to send information to the sensor nodes. The server sends data to the target sensor node

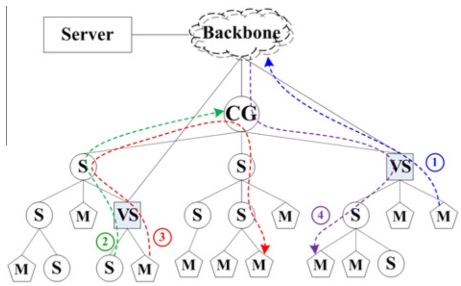

Fig. 6. Conceptual design of the VS node based sensor network.

even if the target sensor node is a descendant of the VS node. In this case, the VS node executes in the same manner as legacy stationary nodes.

4.3.2. Software architecture of the VS node

Fig. 7 shows the structure of the VS node software that this paper proposes. The VS node is composed of two modules; each one is responsible for the wireless sensor network and the backbone network, and the VS middleware that connects the two networks. The blue arrowed line (marked ①) means the data flow for the traditional stationary sensor network application such as gathering environmental sensing data. All software components in blue line are the standard Zigbee and IEEE 802.15.4 MAC related. The red line (marked ②) is the data flow between mobile and VS using the proposed BLIDx protocol and middleware supporting priority based packet handling. The component in the red line related with the two functions; one is the gateway function between the wireless (802.15.4 MAC)/wired protocol (Ethernet based TCP/IP) conversion and the other is the access point for the bidirectional communication link between mobile to VS even though the priority based packet handling.

The sensor network module consists of the physical layer, wireless MAC layer, and network layer in the wireless sensor network protocol. The physical layer has the same physical structure as the wireless sensor network and is in charge of the wireless communication within the network. The network layer supports the compatibility of the different stationary nodes, supporting network management and multi-hop routing functions. Hence, a VS node can be recognized as a stationary node that uses wireless sensor network protocol. The Wireless MAC layer consists of the Legacy Wireless MAC Manager, Wireless VS Manager, Packet Monitoring Manager, and Priority Packer Repository (PP Repository). The LWM Manager receives the data from the PM Manager and processes it in the same manner as a current wireless MAC layer does. The PP Repository prioritizes the data according to its type and processes it according to the given priorities. The PM Manager analyzes the data received from the physical layer and determines whether it is to be pumped or not and sends the data that is selected to be transferred via the wireless sensor network to the LWM Manager. The WP Manager pumps the VS data into the PBE Channel in the middleware according to the priorities set by the PP Repository. The WP Manager sends the acknowledgement that is required for accurate data transference in the wireless sensor network to the source sensor nodes.

The backbone network module consists of the backbone physical layer, backbone MAC layer, and the backbone network layer. The backbone network module is responsible for maintaining the physical connection between the servers and the VS node through the backbone network by sending the data that needs to be pumped in the wireless sensor network to the server via the backbone network.

The VS Middleware consists of the Priority based Event Channel (PBE Channel), Backbone Connection Manager (BC Manager),

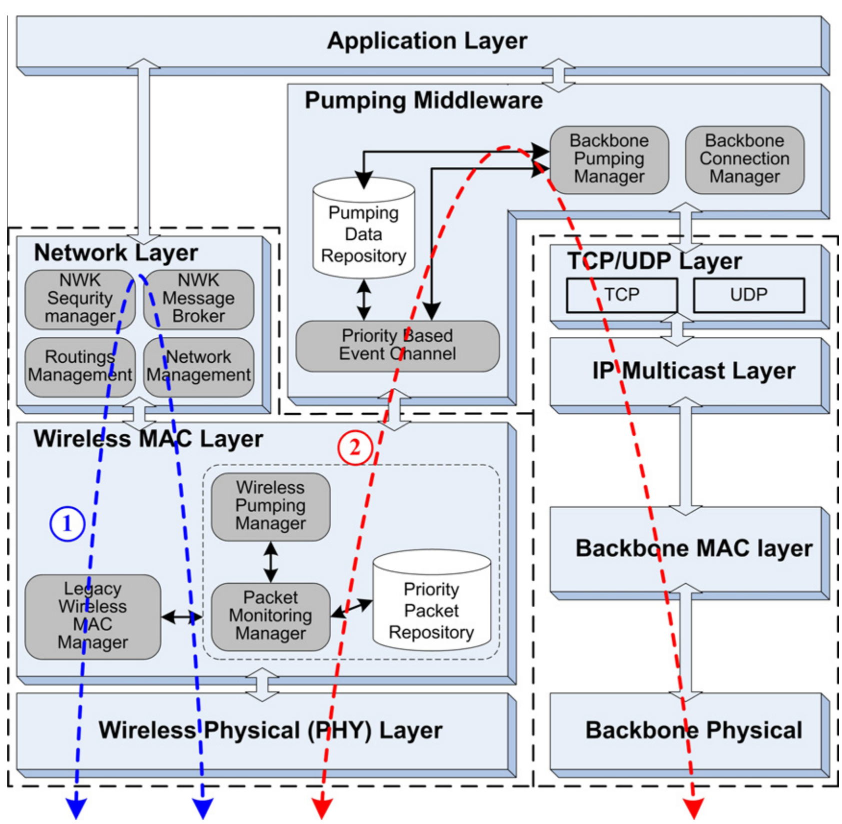

Fig. 7. uMATI software component for the proposed VS node.

Backbone VS Manager (BP Manager), and the VS Data Repository (PD Repository). The BC Manager establishes and maintains the connection to the server in order to send the pumped data to the server via backbone network. The PBE Channel sends the data received from the WNP Manager in the physical MAC layer to the BP Manager. Then, the BP Manager determines the priorities of the received data and sends the higher priority data to the server via the backbone network. However, in the case of a lower priority data, instead of sending it separately, it is stored in the PD Repository until the stored data exceeds its limit or a certain period of time has passed after which it is sent to the server. Because of the bandwidth difference between the wireless sensor network protocol and the backbone network, sending just a single unit of data to the backbone network will waste its bandwidth. Therefore, this method of storing data and sending it altogether is a more effective way of using the backbone network's bandwidth.

The arrowed line ① in Fig. 7 shows the case of data that the VS node received, but did not pump, thereby returning it to the wireless sensor network. Through the physical layer in the VS node and the MAC layer, it is routed in the network layer and sent back to another sensor node through the wireless sensor network. The arrowed line ② depicts the flow of the data when it is sent to the server after being pumped by the backbone network bypassing the wireless sensor network.

5. Experimental evaluation

5.1. Experimental analysis

To evaluate the proposed uMATI architectural prototype, we implemented a test bed with numerous mobile and stationary nodes. The composition of the three-tired uMATI architecture designed to evaluate the performance of the proposed system in the experimental test environment is following: the ZigBee [9] was used as the protocol for the sensor network tier, the Ethernet with TCP/IP for the backbone network tier, and the BLIDx for the mobility tier. The ordinary stationary (OS) node and the mobile node commonly used TI's CC2430 which includes an 8051 MCU Core and a 2.4 GHz RF Transceiver. The mobile node was designed to install into any mobile items and detect activity behavior and location of the embedded mobile object and equipped with an accelerometer sensor, a tilt sensor, and a temperature sensor to undertake such functions. In addition, the BLIDx protocol was implemented at the top of the IEEE 802.15.4 MAC standard and installed both mobile nodes and stationary nodes.

- BLIDx elapsed time measurement between multiple mobile nodes and stationary nodes

Fig. 8 shows the test bed of 50 mobile nodes communicated with 1–4 stationary nodes. A stationary node is directly connected to an Ethernet based gateway and measures the BLIDx performance using a laptop directly connected to the gateway. In the uMATI architecture, one of the most important performance criteria is the number of the mobile nodes that can simultaneously exchange their location ID information (BLIDx) to stationary nodes. Because we used the same hardware and same firmware based on 802.15.4 MAC in both stationary and mobile nodes, we easily achieved the simplicity of manufacturing and low power design of both stationary and mobile nodes. Therefore, we had to check the elapsed time of BLIDx between multiple mobile nodes and stationary nodes to estimate the number of mobile nodes that can simultaneously identify their locations in real-time.

According to the BLIDx protocol (see Fig. 5), each mobile node broadcasts the SID request packet to the surrounding stationary nodes and receives the listener's echo with their ID information within SID wait time delay and the number of retry counts. The test was initiated by varying the SID wait time while several neighboring stationary nodes existed within the RF range of the mobile node.

Fig. 9 shows the BLIDx time in relation to the increasing SID wait time and the number of stationary nodes. At the range of 50–60 ms, the BLIDx performance shows the best within 1.4 s. This implies the high rate of delivery loss occurring in the range faster than the 50 ms due to the physical RF congestion, thereby consuming longer time to complete BLIDx procedure for all mobile nodes

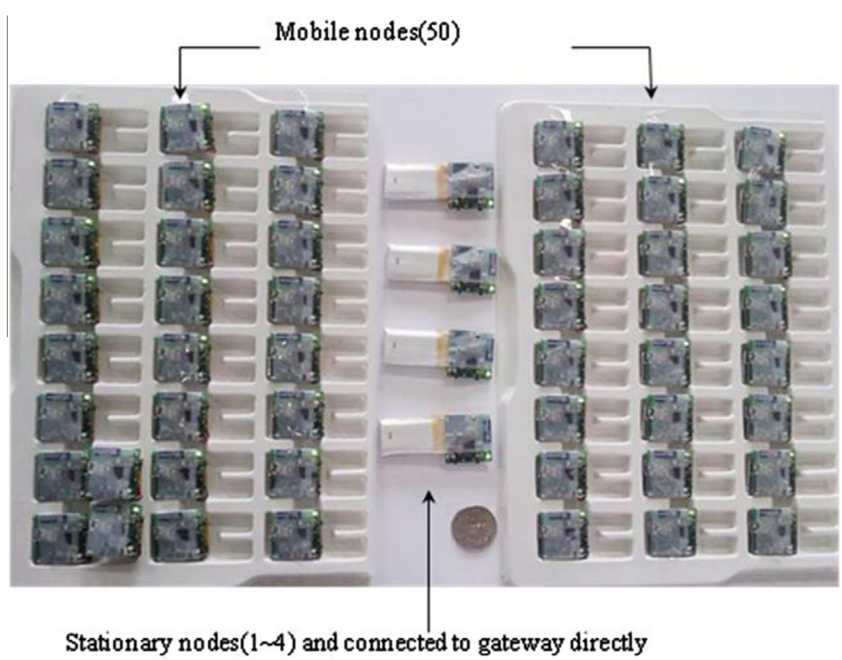

Fig. 8. BLIDx performance test bed (50 mobile nodes and 1–4 stationary nodes).

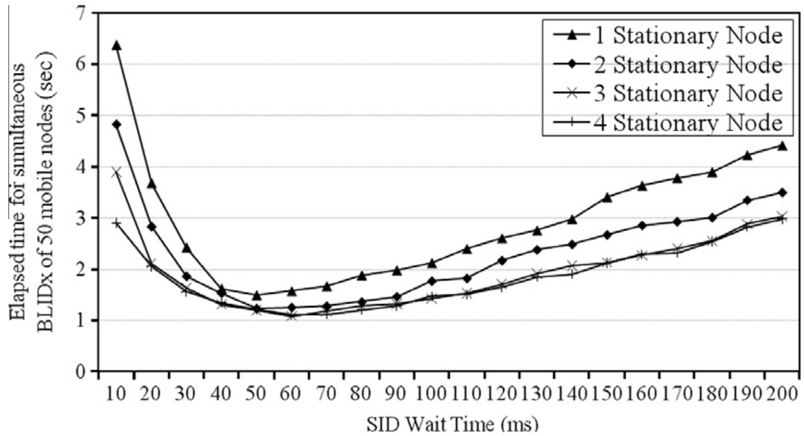

Fig. 9. Elapsed time of simultaneous BLIDx of 50 mobile nodes according to SID wait time.

(50 nodes). In addition, we tested the load balancing effect when there are more than one stationary nodes existed. As shown in the Fig. 9, if one to four stationary nodes existed within same RF coverage range, then the mobile nodes select a dominant stationary node for BLIDx. Due to this property, the load balancing effect is not distinct in this case. According to this experiment, we reached the resolution that if 50 mobile nodes required the location-aware in real-time, the optimal frequency of location-identification interval is the 50 ms without considering the higher tier delay such as multi-hop delay in sensor network tier and communication delay in backbone tier.

In order to check the scalability of the proposed architecture, we additionally test the two factors: one is the maximum number of mobile nodes on a PAN, and the other is the battery life-span of a mobile node according to the periods of the BLIDx. Using the BLIDx performance in Fig. 9, we could calculate the theoretically estimated number of mobile nodes simultaneously covered in a 802.15.4 based PAN. To wrap up BLIDx data in Zigbee packet, we designed the maximum Zigbee packet size after a BLIDx is 36 bytes including all headers. Under assumption that all the mobile nodes are well-distributed around stationary nodes in the PAN (maximum number of mobile nodes per a ordinary stationary node was shown in Fig. 9, and the worst case can be considered using the VS node and the performance shown in the next paragraph), the bottle-neck of the traffic due to the BLIDx might have occurred in the stationary nodes (router nodes) near the coordinator gateway (CG). The max bandwidth of the Zigbee in any path is limited in 256Kbps (2.5 GHz, 802.15.4 standard), but it includes the Rx, TX and ACK packet traffics. We set the maximum bandwidth to cover the BLIDx data is the half of the maximum Zigbee bandwidth (about 125Kbps) in any path of Zigbee based PAN because BLIDx packet also needs Rx, Tx simultaneously. Therefore, we can conclude that when the locations of mobile nodes are identified in the frequency of 1 sec period, maximum 400 mobile nodes can be covered in real-time. In the 1 min frequency, the maximum coverage of estimated mobile nodes is 26,040 nodes. We can conclude here, the 1 min frequency of the location identification of a mobile node is not so bad in the typical mobile asset tracking applications and thus the simultaneous supporting of more than 20,000 mobile nodes are great performance be possible to deploy in real-fields. Fig. 10a shows the result of this theoretical calculation based on the BLIDx periods. However, as we did not include the worst case when too much mobile nodes crowded in the area of a leaf node (stationary leaf nodes in Zigbee PAN) in this experiment, we resolved the virtual sink (VS) node to widen the leaf node bandwidth caused by the single location concentration of numerous mobile nodes in the following sections. Fig 10b shows the average battery life-span of each mobile nodes according to the varying periods of the BLIDx. The battery life-span is one of the most important factors to decide the scalability of the proposed architecture because we used the bi-directional communication media and the long communication distance ($\sim$100 m) comparing with the one-way and the short distance ($\sim$1 m) RFID solution[7]. Using the 1000 mAh capacity of lithium battery, we could extend the

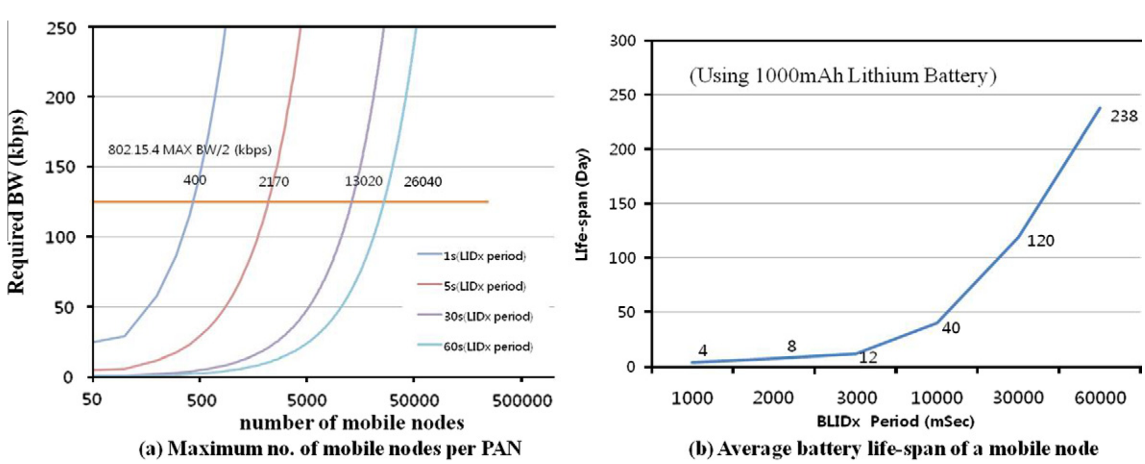

Fig. 10. Scalability test: (a) accommodation capacity of mobile nodes in a PAN, (b) average battery life-span of a mobile node.

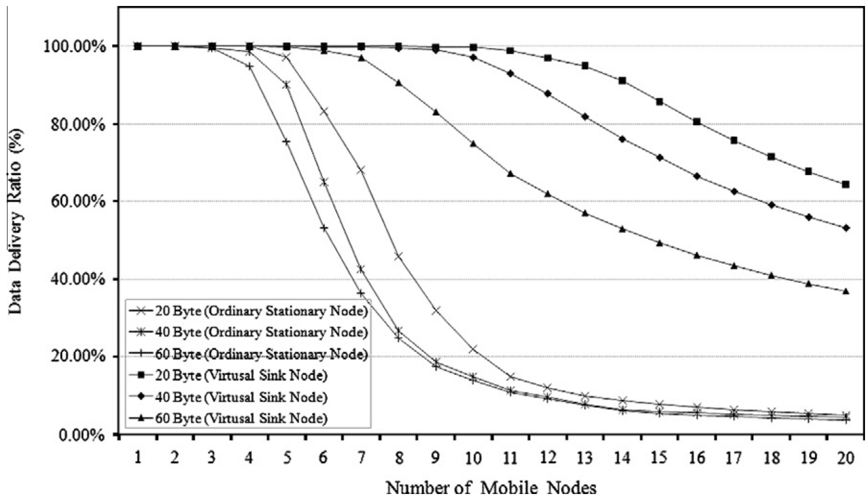

Fig. 11. Delivery ratio of the VS node and OS node.

effective life-time of the mobile node to nearly 1 year if we set the BLIDx period to 1 min and the 1 min of the location tracking time is enough in the majority case of location tracking applications.

- VS node performance compare with OS node

The virtual sink (VS) node was designed to function in the same manner with the ordinary stationary node, but the VS node has a Ethernet to directly send the data from mobile nodes (including BLIDx) to the sink node through backbone network (Ethernet). For this purpose, the VS node consists of embedded ARM9 MCU, RF transceiver (CC2420), Ethernet interface, and several sensors. Ubinos [35], which is a fixed priority base fully preemptive RTOS, is used for VS node and gateway. In order to evaluate the performance of the VS node, the proportion of the data that was successfully transferred in increasing communication traffic was measured. Because the backbone network had a much wider bandwidth than that of the wireless sensor network, the probability of the successful data transference was determined by the performance of the wireless sensor network rather than the backbone network. As mentioned before, when the VS node does not pump, it performs in the same manner as an OS node. In order to compare this with the OS node in the ZigBee network, the evaluation was done while the number of mobile nodes and the ZigBee application payload were varied. Each mobile node was set to send the data in 50 ms cycles. The Fig. 11 shows the success rate of data delivery as the number of the mobile nodes increased. It was evident that when there were a small number of mobile nodes there was no difference between the success rate of the VS node and the router node. However, as the number of mobile node increased the rate of the router node declined rapidly.

- Multi-hop based priority packet performance analysis (including VS node)

Fig. 12 shows an example of the experimental configuration to verify the performance of priority packet from source mobile nodes to destination mobile nodes or server-side. The performance between multiple mobile nodes to a stationary node including virtual sink node was mentioned in the previous paragraphs (Fig. 9 and Fig. 11), therefore, we will mention the performance of multi-hop based priority packet delivery between source stationary to destination stationary.

Based on the proposed three tiers architecture, the virtual sink node is a stationary node stretch over sensor network tier and back bone tier, so it could be let in any node of the multi-hop. The 1 hop test is already performed in the Fig. 10, and to simplify this test, we

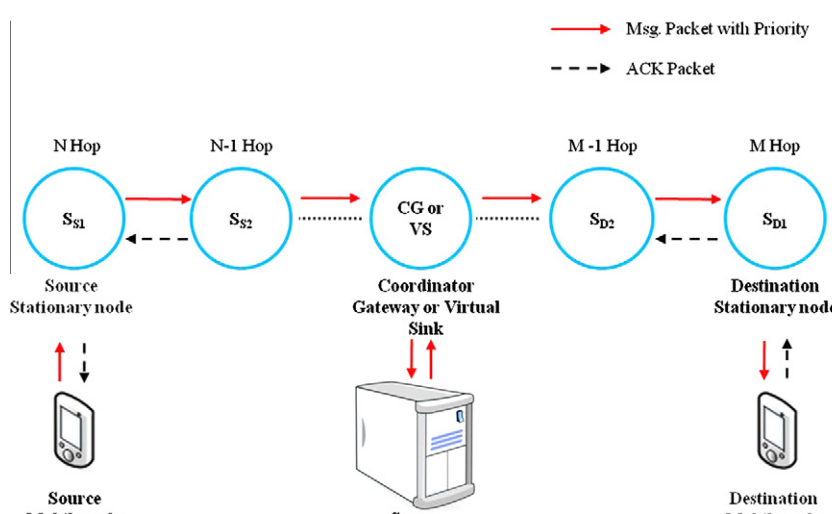

Fig. 12. Multi-hop based message packet delivery procedure.

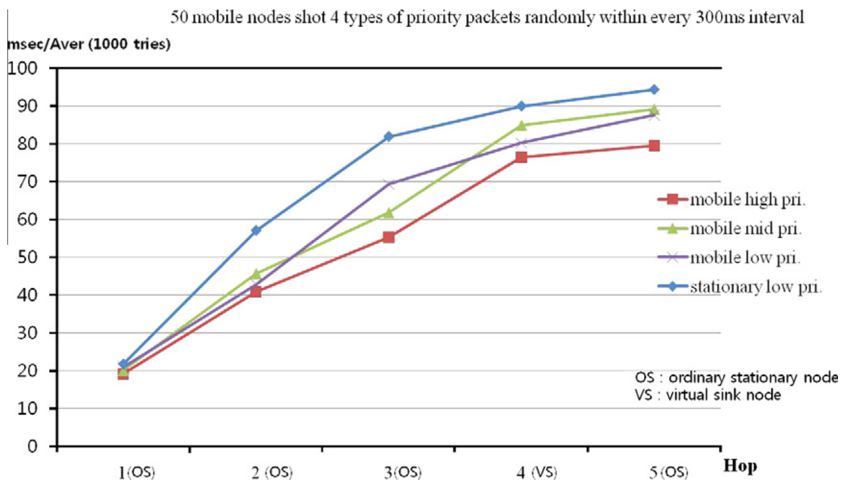

Fig. 13. Performance evaluation of priority packet delivery on multi-hop test bed.

will attach a VS node at the end of the testing multi-hop before destination OS as shown in Fig. 13.

Under this example experimental configuration, the 50 source mobile nodes those are located in S_1 sends 3 types of priority packet randomly with in every 300 ms interval. The meaning of the priority is mentioned in Section 4.2.4 and Table 1. And additionally, as a lowest packet, S_1 also send a packet with same period to the same destination. The performance of the destination stationary to destination mobile was already reflected to the previous test, so it is not included in this test.

Fig. 13 shows the performance evaluation of the priority based packet delivery service in multi-hop environment include a VS node. It was assumed that the single hop communication delay between stationary node and mobile node is constant. This graph represents the average delay between source stationary node and destination stationary nodes after completing one thousand tries. Because of various environmental factors, the results are varied, but the overall performance can be understood from the graph. The communication delay between source and destination stationary node increased as hop-depth is deeper and the delay also varied according to packet payload. However, the worst delay between source and destination was less than 100 ms which means that the packet handling protocol ensures that all types of priority packets can be delivered to the destination at a deterministic time. In spite of the priority processing in the each nodes, we didn't implement the priority concept in the low layers of MAC (purely use the CSMA/CA based 802.15.4 standard), therefore, when collision occurred at the lower layers of MAC then they always retry to send the packet. Due to this situation, the effect of the internal and above MAC layer priority handling is very little in the OS node but in the case of VS node, because it use the fully preemptive priority based RTOS with much main memory, the priority effect can be slightly measured as shown in the range from 4 hop (VS) to 5 hop (OS). The mobile_low_pri packet arrived little-bit faster than the mobile_mid_pri packet despite of low priority at the front side of VS but the gap is shortened at the 5 hop due to the prior service by the VS node.

5.2. Comparison with legacy WSN protocol for location tracking applications

As the above experiment shows, it was confirmed that when the SID wait time was set at 50 ms and the number of retries was set at 1, the mobile node recognized all the stationary nodes through the BLIDx. The SID wait time in ZigBee [9–11] was set at 800 ms and the number of retries 3 as default while end device joined the ZigBee network. Fig. 14 shows that the SID wait time had a significant influence on the ability of the mobile node to transfer its location information to the server and even if the SID wait time was increased to 200 ms, the 50 mobile nodes' BLIDx and location information transference to the server could be done in 1.6 s.

Fig. 14 shows that the association time between mobile nodes and OS nodes using ZigBee Join, BLIDx (800 ms duration, 3 retries), and BLIDx (50 ms duration, no retry). The BLIDx performance was always better than the ZigBee Join. The test results show that when SID wait time decreased, SID recognition declined. When the opposite happened, the amount of time used to send the location information to the server increased. Hence, the recognition of the mobile node and the time spent to transfer data had to be determined at the level that could utilize this trade-off. It will be decide each recognition time for adopting acceptable performance with SID wait time increasing.

6. Conclusion

This paper proposes the three-tier WSN middleware architecture. The proposed system has been designed to minimize the impact of mobility on basic service and the recognition of the location of the mobile node by the stationary node while the mobile nodes are on the move in the wireless sensor network environment. This system is composed of a mobility tier to provide mobile node mobility, a sensor network tier that forms the network along with

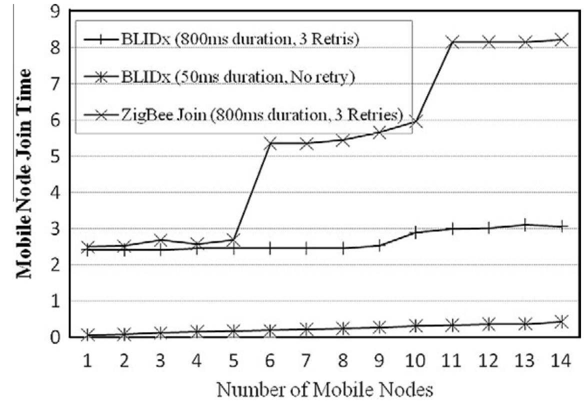

Fig. 14. Comparison of mobile node association time using ZigBee JOIN vs. BLIDx.

the stationary nodes, and a backbone network tier that is connected to the server.

The mobility tier, as mentioned, provides the flexible mobility of the mobile nodes and reduces network reconfiguration caused by the frequent movement of mobile nodes. Mobile nodes and stationary nodes communicate with IEEE802.15.4 MAC communication while they share the same physical and MAC layer as well. Therefore, they could be identified as heterogeneous networks in the network layer, but they are identified as a homogeneous network in the physical and MAC layer. Utilizing this, it was possible to minimize the impact on sensor network reconfiguration with mobile nodes that did not use the network protocol and mobile nodes that only influenced the physical network conditions when they held a communication channel.

To address the problem of traffic intensity, congestion, and high packet loss due to a high density concentration of the mobile nodes in a single location, we proposed the usage of a VS node that was embedded with a wide-bandwidth network interface and the features of legacy stationary nodes that undergo the same procedure as the other stationary nodes do. The VS node analyses the passing data, transforms the data that can be pumped, into a form that is suitable to the characteristics of the backbone network, and sends it to the server through the backbone network. Employing the VS node reduces the upstream traffic, thereby addressing the problem of the sensor networks' bandwidth narrowness.

Based on the performance evaluation of the proposed uMATI architecture, we can suggest the uMATI as a realistic solution of mobile asset management service with the following advantages:

- Fully utilizing the real-time tracking service despite of numerous mobile nodes by adopting fast and simple BLIDx protocol.
- Reducing the manufacturing cost by adopting the compatible low level protocols and hardware both stationary nodes and mobile nodes.
- Solving the traffic overflow due to the unpredictable congestion of numerous mobile nodes into a single location using VS node.
- Supporting the priority based event packet delivery by classifying and differentiated handling the packets according to the external priority of the events (see Table 1).

Acknowledgments

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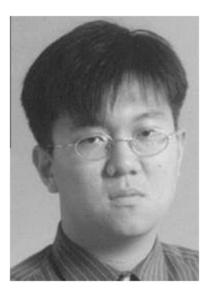
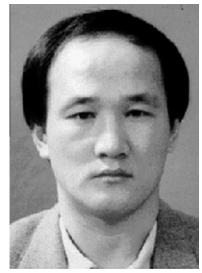


Dong-Kyu Lee received his BSc degree, MSc degree, and Ph.D. degree in school of electrical engineering and computer science from Kyungpook National University, Daegu, Korea, in 2002, 2004, and 2010, respectively. He is currently working at LG Electronics. His research interests include real-time and embedded system, wireless sensor networks, and reconfigurable software and hardware.

Tae-Hyon Kim received the BSc degree, MSc degree in school of electrical engineering and computer science from Kyungpook National University, Daegu, Korea, in 2005 and 2007, respectively. He is currently working toward the Ph.D. degree at Kyungpook National University. His research interests include real-time operating system, wireless sensor networks, and opportunistic computing.

Seol-Young Jeong received the BSc degree in computer engineering from Donga University, Busan, Korea, in 2001, and the MSc degree in computer education from Keimyung University, Daegu, Korea, in 2009. She is currently working toward the Ph.D. degree at Kyungpook National University. Her research interests include real-time operating system, wireless sensor networks, in-vehicle network, and reconfigurable software and hardware architecture.



Soon-Ju Kang received the BSc degree in electronics from Kyungpook National University, Daegu, Korea, in 1982, and the M.S. and Ph.D. degrees in computer science from Korea Advanced Institute of Science and Technology (KAIST), Daejon, Korea in 1985 and 1995, respectively. From 1985 to August 1996, he worked at Korea Atomic Energy Research Institute (KAERI) as a member of research staff and a head of computing and information research department. Since September 1996, he has been a faculty member of School of Electronic Engineering and Computer Science of Kyungpook National University. Meanwhile, he also worked at University of Pennsylvania, Philadelphia as a visiting research faculty from 2000 to 2001 and 2007 respectively. His current research interests include embedded real-time system, home network, distributed object technology and software engineering. He wrote 7 books related in embedded systems as a co-author and published about 70 technical papers in regular international journals and related conferences. Dr. Kang is a member of IEEE computer society, ACM, KISS, KIEE, KITE.