An Energy-Efficient Positioning-Enabled MAC Protocol (PMAC) for UWB Sensor Networks

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Abstract—**This paper proposes a positioning-enabled medium-access control (PMAC) protocol designed for UWB wireless sensor networks. The medium access protocol consists of a fully, distributed, self-organizing TDMA scheme which supports localization. The new protocol is flexible while at the same time fulfilling the basic requirements of low energy consumption, limiting latency and maintaining high data throughput. The protocol is suitable for use in ad-hoc networks where mobility and changes of network density have significant impact.**

I. Introduction

Management of wireless communication will be the key to effective deployment of large scale sensor networks that need to operate for long period of time. Collaboration between neighboring sensor nodes overcomes the inherent limitations of their low cost, and hence limited capabilities. Cooperation between nodes also allows significant range extension through data relaying to a gateway node connected to the wired world.

Ultra-wideband (UWB) technology has generated significant interest in recent times for both the very-high data rate (VHDR) as well as the low data rate (LDR) scenarios [1]-[3]. Emerging applications of UWB are foreseen for sensor networks as well. Such networks combine low to medium rate communications with positioning capabilities. UWB signaling is especially suitable in this context, because it potentially allows centimeter accuracy in ranging, as well as low-power and low-cost implementation of communication systems. Such precise positioning information can be utilized to develop location-aware networking. In other words, improved co-existence with other piconets/systems and reduced power consumption can be achieved by scaling personal operating space based on UWB localization. The evolution of UWB physical layer techniques has also sparked the interest of groups working in the MAC issues. A great deal of support is required from the MAC layer if the inherent advantages of UWB systems are to be realized by the user. Currently, there are no UWB MAC standards that directly address the issue of localization.

In this paper, we propose a simple, time division multiple access (TDMA)-based, positioning-enabled MAC protocol, which supports both localization and energy efficiency. This protocol does not rely on base stations or a central manager, supporting a self-organizing, dynamic network topology making suitable it for wireless ad-hoc networks. The concept is to allow the efficient transmission of short omni-directional messages between the UWB nodes and the higher networking layers which carry local topology knowledge to the upper layers. The MAC protocol also allows nodes to have knowledge of their physical area and position of operations, which will then enable the efficient, relaying and transferring of messages and data to its destination. Furthermore, the localization capability will also provide mobility-awareness and optimization of the network.

The remainder of the paper is set out as follows: Section II defines the network structure assumptions used; Section III provides the related works on TDMA-based protocols. The design overview of our protocol (PMAC) is covered in Section IV, beginning with the description of the frame structure of the time slot and the functions packed in this protocol. The position request criteria and node descriptions will also be included.

II. TDMA-based MAC protocols

Protocols for Wireless Sensor Networks (WSN) are broadly divided into two approaches; contention-based [14]-[15] and schedule-based [7]-[13]. TDMA systems are inherently good at energy conservation since, during the time slot where a device is not actively engaged in communication, it may enter a low power “sleep mode” and turn off its transceiver. In general, a node in a sensor network, where there is low-activity, is required to stay awake for one time slot within each frame to receive the traffic control information. There are various TDMA-based protocols proposed mentioned in the literature [7]-[13]. These protocols have different approaches in utilizing the TDMA concept, such as *Sink-based scheduling* approach taken by Arisha [7], rotating duties approach used in the *Power aware clustered TDMA (PACT)* [9], the *Bit-map-assisted (BMA)* protocol [10], which uses the *Low energy adaptive clustering hierarchy (LEACH)* approach [11] and the partitioned scheduling approach used in the *EYES-MAC (EMAC)* [12] and *Lightweight MAC (LMAC)* [13] protocols by Hossel et al.

III. network structure Assumptions

The design and descriptions of our protocol is specifically targeted for use in wireless ad-hoc networks. Three nodes types are deployed in the Ad-Hoc network scenario; namely anchor, bridge and sensor node. The capabilities of the anchor, bridge and sensor nodes are different to facilitate the position calculation and network management. The topology is expected to be completely random where nodes are scattered in an area.

A. Characteristic of Nodes

The characteristics of the nodes are displayed in Table I of this section. The nodes are arranged hierarchically in terms of control and capability as illustrated in Fig. 1.

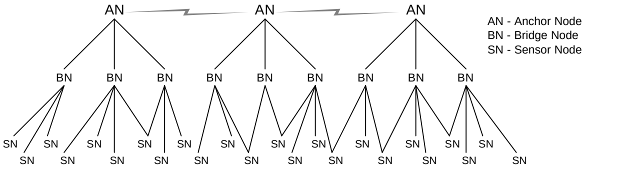

Fig. 1. Hierarchical structure of the nodes in terms of their capability and roles.

TABLE I
ROLES AND DUTIES OF NODES

Node type	Operation modes	Descriptions
Anchor Node	Dynamic, Passive	• Highest Complexity and computational capability. • Position reference for bridge and sensor nodes. • Able to perform position estimation calculation. • Most probably function as a gateway to other network. • Operate mostly in dynamic mode. • Operate in passive mode only when there is low activity.
Bridge Node	Dynamic, Passive	• Lower complexity and computational capability • Position reference for sensor nodes • Able to perform only low complexity position estimation calculation • Gateway and relaying points between virtual clusters • Switch regularly between dynamic and passive for energy conservation • Operation mode is dependent on node density and traffic.
Sensor Node	Dynamic, Passive, Snooze	• Low complexity and low cost • Obtain position from bridge node • Transmit via bridge or anchor nodes • May function as a simple relay node in dynamic mode if required • Operates normally in passive mode • Operates in snooze mode if node activity is very low.

B. Virtual Cluster

A network of wireless sensors, consisting of anchor, bridge and sensor nodes, is divided into smaller groups known as virtual clusters (VC) as illustrated in Fig. 2. These VCs have a dynamic nature, where the shape and size of the cluster changes over time. These factors are dependent on the number of anchor and bridge nodes, their location, and the coverage area. There is a tendency for these clusters to overlap, sharing a few bridge nodes between the clusters. By keeping the coverage area of the VC small, nodes in a cluster can utilize lower transmit power due to the reduced distances between nodes.

Position estimation is performed within these VCs using various position estimation algorithms [4]-[6]. Most of these algorithms require at least three or four reference points to perform a 3-D position estimation of a particular node. Therefore, a criterion is set that there should be at least four dynamic nodes in each of these VCs. An anchor node can act as a bridge node when there are insufficient bridge nodes in the neighborhood to form a VC. Sensor nodes that are within range of these nodes will fall into this VC and will be able to send data through these nodes.

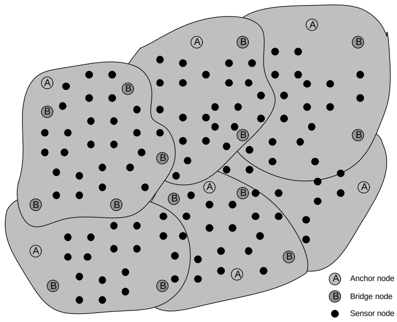

Fig. 2. The VCs are free-form according to the location of the bridge and anchor nodes and overlapping of cluster is possible.

IV. DESIGN OVERVIEW FOR PMACS

In this paper we explore a medium access protocol whose operation is entirely distributed and localized. Some of the MAC protocols proposed have inherent restrictions on network changes and structures. The approach is similar to EMACS presented in [12] and LMACS presented in [13] where partitioned scheduling is implemented. However, both of these protocols do not cater to localization. The nodes operate in three different modes: dynamic, passive and sleep modes as described in Table I. When the node is in dynamic mode, it will contribute to a network of nodes, which form the backbone for data relaying and transferring to a particular destination by accepting data from passive nodes. When nodes operate in passive mode, they conserve energy by only keeping track the dynamic nodes in its VC, which can provide forwarding service for their data and providing them with network wide messages.

A. Time slot

This sub-section will provide an overview of the frame structure, which is based on TDMA. Each frame is divided into time slots that nodes can utilize to transmit data contention free.

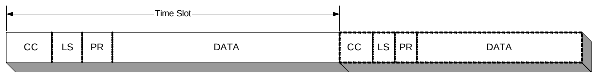

Fig. 3. The PMAC time slot consists of 4 sub-slots: i) Communication Control, ii) Link Setup, iii) Positioning Request and iv) Data (Payload)

Each of these time slots (Fig. 3) is further subdivided into 4 sub-slots: Communication Control (CC), Link setup (LS), Positioning Request (PR) and Data. A CC message is transmitted to provide the neighboring nodes with the control and synchronization information, such as resource availability and slot scheduling table. Within the LS slot, the particular passive node will send a transmission request (TR) to the listening dynamic node to request for data transmission and the dynamic node will provide a possible acknowledgement in return. The PR slot is used when a node requires the dynamic nodes in the cluster to perform a position estimation operation. The remainder of the time slot (data section) is used for data transfer. Nodes will rotate their duties, being dynamic and passive, for energy conservation however, a minimum number of nodes must be in dynamic mode within a VC to form the backbone of the WSN. A passive node does not control a time slot and is therefore able to conserve energy as it only listens and transmits when required.

B. Communication Control

Communication control (CC) sub-slots are used to provide control information to the sensor node within its VC. Every dynamic node in the VC transmits a CC sub-slot in its assigned time slot. The CC is transmitted by a dynamic node at the start of the time slot to provide the passive sensor nodes with control information (Table II).

TABLE II
COMMUNICATION CONTROL SUMMARY

Control Information	Function(s)
ID	Dynamic node identifier
Time slot table	Contains the time slot allocation information in the area
Synchronization information	Sequence for clock synchronization of neighboring nodes.
Transmit Information	Used for indicating data transfer to a particular node.
Status	Indicator for operation mode and status change

A new node entering the VC can use the synchronization information to synchronize its clock to the dynamic nodes. The nodes around the dynamic node will listen to the CC to obtain the ID of the dynamic node as well as the available time slots. When a dynamic node has data to transfer to its neighboring node, it will address the node using the transmit information and thereafter it will send the data to the particular node. Other neighboring nodes will know from the CC that the dynamic node is busy and will not submit a Transmit Request (TR) the dynamic node. When the dynamic node is ready to move into passive mode, it will inform the neighboring node using the status flag. A passive sensor node will have the knowledge of the nearest dynamic bridge node by listening to the CC and either estimating the signal strength or the TOA of the signal. The sensor node will set a priority flag for each of the bridge node and will send their data through the node with the highest priority. If the bridge node is busy, it will send through the node with the next highest priority.

C. Link Setup

The link setup (LS) is used by the passive nodes to submit their intentions to transmit data using the active time slot. The link setup contains the information summarized in table III.

TABLE III
LINK SETUP SUMMARY

Control Information	Function(s)
Transmit request (TR)	Node ID sent to Dynamic node requesting for data transfer
Request information	Contains information such as transfer size and destination.
Collision Flag	Indicator for collision
Acknowledgement Flag	Indicator for displaying the status of the TR

The TR in the LS is essential to ensure that the data sent is not corrupted in the cases where more than one node has the same intention. The dynamic node that owns the time slot will then inform the nodes of a collision flag in its reply. When a collision occurs as a result of multiple requests, nodes listening to the LS collision flag will back off for a specific time before attempting to resend the data. If only one node sends a request, and the time slot is available, the dynamic node will send an acknowledgement to the listening node and thereafter proceed with the data transmission using the active time slot.

D. Positioning Request

The positioning request (PR) sub-slot is dedicated to positioning and can be accessed by any node that requires a position update. Data transmission operations will not interfere with the same time slot. The PR will contain information as summarized in Table IV.

TABLE IV
POSITION REQUEST SUMMARY

Control Information	Function(s)
ID	Identifier of Node that require position update
Request type	Contains information indicating the purpose of position update
Request Status	Indicator for displaying the result of position request
Collision Flag	Indicator for collision

The request will be in the form of its ID and request type. This request will also be broadcast to the other dynamic nodes around the neighborhood of the requesting node. Upon receiving the request, Time of Arrival (TOA) or Time-difference of Arrival (TDOA) estimation will be performed and the results will be consolidated in an anchor or bridge node for position estimation calculations. The request type states whether the position update is an update of an expired position information, a change of its physical position or a subsequent request as the node is still in motion. The status of the position estimation will be addressed with the request status. In the event of a collision, the collision flag will inform the node of the collision and request for a retransmission in the next available time slot or after a pre-determined time. The positioning request criteria are laid out in sub-section G.

E. Data Sub-slot

The data sub-slot takes up the largest portion of the time-slot. This sub-slot is reserved for the transfer of payload data between nodes. Data from the neighboring nodes can be combined and transferred with an addition mechanism for the combination process.

F. Selection of Time Slot

Bridge nodes will stay in dynamic mode for a pre-determined amount of time or as required. The passive bridge node will use the knowledge of the information in the time slot table sent in CC to search for a free time slot (Fig. 4). When more bridge nodes are needed, the passive bridge nodes will be alerted to switch to dynamic mode and will select a time slot from the table of time slot sent by neighboring dynamic nodes.

The selection of time slot process is the same as EMAC [12]. However, sensor nodes do not control any time slots in PMAC, only the bridge and the anchor nodes can control time slots. As a result, sensor nodes will conserve energy and will send data through the bridge and the anchor node. The time slot table in the CC will contain information of the time slots that the node considers to be occupied by it and its one-hop neighbor nodes. Nodes can select a time slot when the slot is free. The time slots will therefore be reused after at least three hops, preventing interference within the same time slot. Collision might occur during the selection when more than one node decided to opt for the same free time slot. The nodes will back off for a random length of time and re-select a slot. Fig. 4 illustrates the selection of a time slot by a bridge node entering a VC or a passive node switching to dynamic mode.

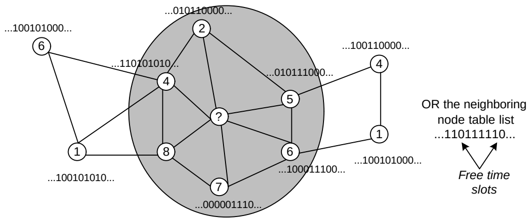

Fig. 4. A bridge node can determine the free slots by studying the time slot allocations of the nodes around it.

G. *Position Request Criteria*

Delay estimation information must to be able to be updated regularly to ensure that device location information remains updated. This has to be done without high overhead as well as a low delay on data transmission. The following are some of the criteria for position request to prevent energy wastage due to unnecessary position estimation and to reserve the PR sub-slot for those nodes that require an update of their position information. They are related to the accuracy requirement and capability, availability of resources and mobility of the node.

Sensor nodes are allowed to send a position request when a pre-determined “validation” period has expired. A refresh rate or validation time has to be determined for each node or network to ensure that the position of the nodes within each VC is current.

When the node is displaced from its initial position, a PR can be broadcast to the dynamic nodes in the VC to initiate the position estimation update process. Three methods can be performed to determine the change of position.

TOA Method - TOA measurement is performed between the sensor node and the dynamic nodes within its VC (Fig. 5). When there are changes in the TOA, a position update is required. However, the TOA changes can also be a result of obstruction and therefore more than one reference must to be used for decision-making. According to the accuracy requirements and capability, there is a buffer for allowable movement known as a *virtual area* (Fig. 6). If the accuracy requirement is low, any position update within this virtual area will not lead to any recognized position changes. When the node moves out of its virtual area, a position request is broadcast to its neighboring dynamic nodes and the position estimation process will be initiated.

Signal Strength - The signal strength of the dynamic nodes can be assessed while listening to their CC broadcast. The sensor nodes will always listen to the CC and when signal strength increases and another decreases, it can be assessed that the sensor is moving towards the dynamic node with a higher signal strength (Fig. 7). The direction of movement can also be detected with this method.

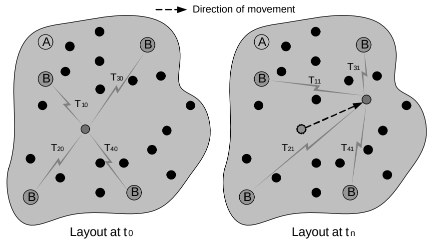

Fig. 5. Movement of a particular node can be determined using TOA estimation (one or two way ranging).

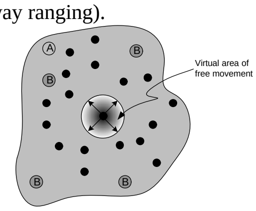

Fig. 6. The size of the virtual area of freedom movement is determined by the accuracy capability of the position estimation algorithm used.

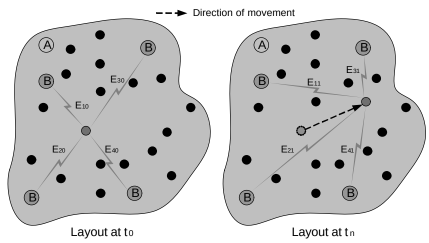

Fig. 7. Movement of a particular node can be determined by listening to the signal from the neighboring bridge nodes, which are getting either stronger or weaker.

Breakage of Communication link - movement can be detected when the moving sensor node loses communication with any particular dynamic node (Fig. 8). When the listening sensor nodes are unable to detect the CC of a particular dynamic node, it means that the node is moving away from the dynamic node. The direction of movement can also be determined from this process; however, movement must be substantial before movement is detected.

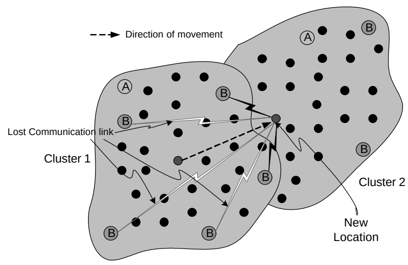

Fig. 8. Movement of node can be determined when there is a breakage of Communication link that means, which the node is moving away from the bridge node(s).

V. RESULTS

We compare the performance of PMAC and TDMA as cluster-based MAC schemes in terms of energy consumption. The results are based on analytical computations. The comparison does not consider the possibility of bit-error in the contention period and the full capability of PMAC. The basic setup is a cluster of N nodes which are made up of bridge and sensor nodes. A fixed number of bridge nodes, K_{BN}, will be considered at this point and therefore no adaptive feature is being implemented. The probability that a node will send data is p.

The energy model being utilized for the nodes is based on the ASIC designed in CWC [16]. The transceiver uses 20 mW for transmitting, 116 mW for receiving, and 0.136mW for idle. The data rate is 24 kbps and we assume a data packet size of 250 bytes and a control packet size of 54 bytes for TDMA and 18 bytes each for CC, LS and PR.

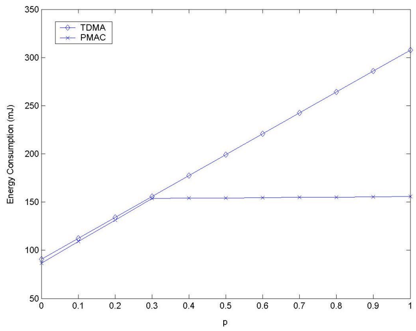

Fig. 9. Average total cluster energy consumption vs. p when $N=20$ and $K_{BN}=6$.

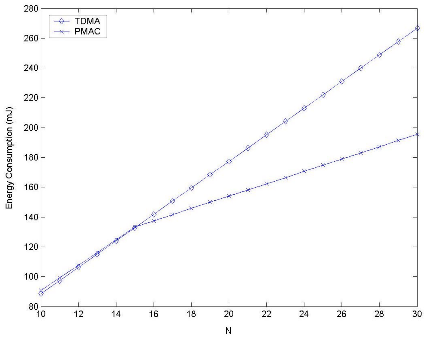

Fig. 10. Average total cluster energy consumption vs. N when p = 0.5, K_{BN}= 6.

Fig. 9 provides a comparison of PMAC and TDMA MAC techniques in terms of the average total cluster energy consumption as a function of p for $N=20$ and $K_{BN}=6$. The energy consumption of cluster is controlled by the number of bridge nodes in the cluster and therefore the plot flattens out when $p=0.3$. Positioning is performed at a probability of 0.5 and the overhead of the synchronization and control sections contribute to energy consumption. Fig. 10 illustrates the impact of increasing the number of nodes within the cluster for p=0.5 and K_{BN}=6. PMAC performs better by regulating the energy consumption and at the same time provide positioning capability. However, this might affect the latency of data transfer and therefore require further investigation.

VI. CONCLUSION AND FURTHER RESEARCH

We have proposed a positioning-enabled medium access control protocol for WSN. The protocol is designed with localization, flexibility and energy-efficiency in mind. This protocol does not rely on base stations or a central controller, which makes it self-organizing and dynamic. Nodes within a WSN are divided into three categories of different complexity and capability.

A sub-slot is reserved within a time slot for positioning request from the nodes that require an update of their position. Position estimation can therefore be performed in any time slot. Our MAC protocol also allows nodes to have knowledge of their physical area and position of operations, which will then support efficient relaying, transferring and routing of data within the network. The localization capability will also provide mobility-awareness and optimization of the network.

Further research will be done in the assessment of the protocol by performing simulations to compare our protocol and existing MAC.

VII. ACKNOWLEDGEMENT

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