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Real-Time Communication and Localization for a Swarm of Mobile Robots Using IEEE 802.15.4a CSS

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***Abstract*—Just-in-time inventory management and short production cycles require flexible material flow as well as usage of small transportation units. These demands can be met by using small Automated Guided Vehicles (AGVs) which act as a swarm of mobile robots. The paper presents real-time communication and localization for a swarm of mobile robots which transport Euro-bins in a distribution center or warehouse. Localization is realized by trilateration using range measurements obtained from an IEEE 802.15.4a CSS network. The IEEE 802.15.4a network is used for communication as well as for localization. The paper presents the design of the networks as well as the communication protocol which provides communication and localization in real-time. In order to support a large number of robots, the whole working area is divided into cells which uses different frequencies. The network protocol provides handover between the cells and routing capabilities in real-time.**

I. Introduction

Just-in-time inventory management and short production cycles require flexible material flow as well as usage of small transportation units. These demands can be met by using small Automated Guided Vehicles (AGVs) which act as a swarm of mobile robots. Several companies have introduced small AGVs for logistic applications. Examples are "The Kiva Mobile Fulfillment System (MFS)" [1] and "ADAM™ (Autonomous Delivery and Manipulation)" [2]. Inexpensive localization of small AGVs is an important issue for many logistic applications and object of current research activities. The Kiva MFS uses bar codes on the floor which can be detected with a camera by the AGVs [1]. These bar codes specify the pathways and guarantee accurate localization. Drawbacks of this solution are the risk of polluting the bar codes and the need for predefined pathways which restrict the movements of the AGVs.

Fig. 1 shows the target application of the proposed real-time communication and localization system. In this distribution center, AGVs transport bins with Euro footprint (600x400 mm) from a high bay racking to order picking stations and back to the racking. Order pickers collect the orders from Euro-bins and pack them into custom bins. AGVs navigate autonomously and act as a swarm of mobile robots. To fulfill this task, real-time communication and localization is needed. The paper proposes the usage of an IEEE 802.15.4a Wireless Sensor Network (WSN) for communication as well as for localization. A WSN consists of spatially distributed autonomous sensor nodes for data acquisition. Besides military applications and monitoring physical or environmental conditions, WSN can also be used for localization. To localize a mobile node, called *tag*, there have to be a couple of nodes with fixed and known positions. These nodes are called *anchors*.

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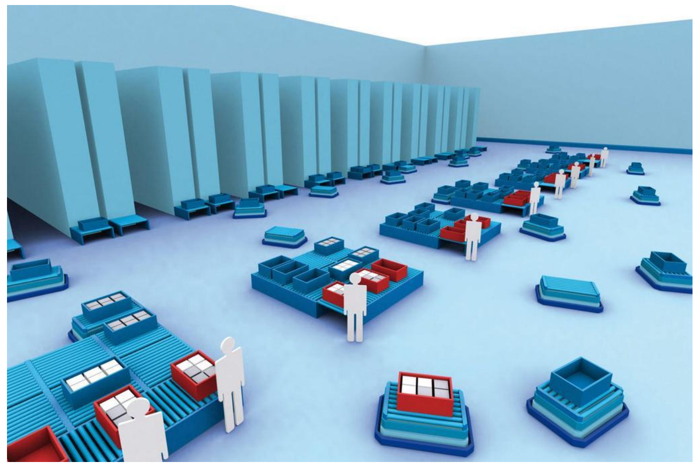

Fig. 1. Swarm of mobile robots in a distribution center © Fraunhofer IML

In this paper a new communication protocol for WSN is developed which is based on IEEE 802.15.4a and provides localization, communication and routing in real-time. Since the data size in an IEEE 802.15.4 frame is limited to 127 Bytes, low overhead of the protocol is one key requirement. Instead of using the superframe structure of IEEE 802.15.4, a new superframe structure is developed, because IEEE 802.15.4 supports only superframes with 16 equally sized time slots.

II. Related Work

Up to now several kinds of localization techniques have been developed for the use in wireless networks. A review of existing techniques is given in [3]. These techniques can be classified by: Connectivity, Received Signal Strength (RSS), Angle of Arrival (AoA), Time of Arrival (ToA) and Round-trip Time of Flight (RToF).

Connectivity information is available in all kinds of wireless networks. The accuracy of localization depends on the range of the used technology and the density of the beacons. In cellular networks Cell-ID is a simple localization method based on cell sector information. In a WSN with short radio range, connectivity information can be used to estimate the position of a sensor node without range measurement [4].

RSS information can be used in most wireless technologies, since mobile devices are able to monitor the RSS as part of their standard operation. The distance between sender and receiver can be obtained with the Log Distance Path Loss Model described in [5]. Unfortunately, the propagation model is sensitive to disturbances such as reflection, diffraction and multi-path effects. The signal propagation depends on building dimensions, obstructions, partitioning materials and surrounding moving objects. Own measurements show, that these disturbances make the use of a propagation model for accurate localization in an indoor environment almost impossible [6].

AoA determines the position with the angle of arrival from fixed anchor nodes using triangulation. In [7] a method is proposed, where a sensor node localizes itself by measuring the angle to three or more beacon signals. Each signal consists of a continuous narrow directional beam, that rotates with a constant angular speed. Drawback of AoA based methods is the need for a special and expensive antenna configuration e.g. antenna arrays or rotating beam antennas.

ToA and RToF estimate the range to a sender by measuring the signal propagation delay. Ultra-Wideband (UWB) offers a high potential for range measurement using ToA, because the large bandwidth (> 500 MHz) provides a high ranging accuracy [8]. In [9] UWB range measurements are proposed for tracking a vehicle in a warehouse. The new WSN standard IEEE 802.15.4a specifies two optional signaling formats based on UWB and Chirp Spread Spectrum (CSS) with a precision ranging capability [10], [11]. Nanotron Technologies distributes the nanoLOC TRX Transceiver with ranging capabilities using CSS as signaling format.

Compared to the large number of published research focused on localization, there is less research on protocols combining localization and communication. In [12] a MAC protocol with positioning support is described. This work is mainly focused on energy efficient medium-access. A MAC protocol combining localization and communication based on IEEE 802.15.4a is described in [13], [14]. The protocol is contention-based and did not support real-time localization. WirelessHART is based on IEEE 802.15.4 and offers real-time communication using TDMA, but it did not support ranging [15], [16].

III. The nanoLOC Localization System

Nanotron Technologies has developed a WSN which can work as a Real-Time Location System (RTLS). The distance between two wireless nodes is determined by Symmetrical Double-Sided Two Way Ranging (SDS-TWR). SDS-TWR allows a distance measurement by means of the signal propagation delay as described in [17]. It estimates the distance between two nodes by measuring the RToF symmetrically from both sides.

The wireless communication as well as the ranging methodology SDS-TWR are integrated in a single chip, the nanoLOC TRX Transceiver [18]. The transceiver operates in the ISM band of 2.4 GHz and supports location-aware applications including Location Based Services (LBS) and asset tracking applications. The wireless communication is based on Nanotron's patented modulation technique Chirp Spread Spectrum (CSS) according to the wireless standard IEEE 802.15.4a. Data rates are selectable from 2 Mbit/s to 125 kbit/s.

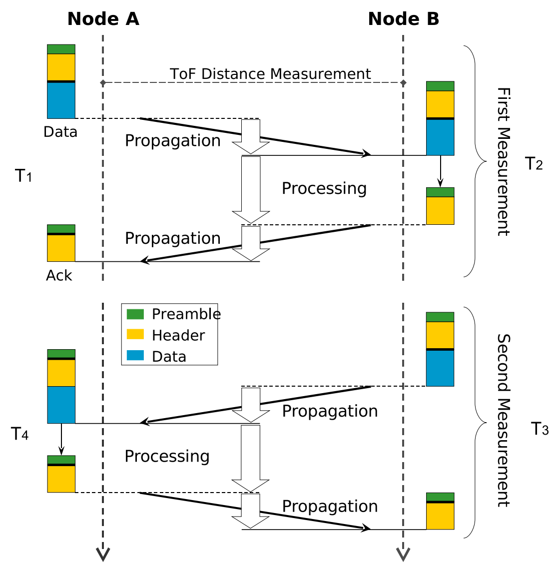

Fig. 2. Symmetrical Double-Sided Two Way Ranging [18]

SDS-TWR is a technique that uses two delays which occur in signal transmission to determine the range between two nodes. This technique measures the round trip time and avoids the need to synchronize the clocks. Time measurement starts in Node A by sending a package. Node B starts its measurement when it receives this packet from Node A and stops, when it sends it back to the former transmitter. When Node A receives the acknowledgment from Node B, the accumulated time values in the received packet are used to calculate the distance between the two stations (Fig. 2). The difference between the time measured by Node A minus the time measured by Node B is twice the time of the signal propagation. To avoid the drawback of clock drift the range measurement is preformed twice and symmetrically. The signal propagation time t_d can be calculated as

$$t_d = \frac{(T_1 - T_2) + (T_3 - T_4)}{4}, \qquad (1)$$

where T_1 and T_4 are the delay times measured in node A in the first and second round trip respectively and T_2 and T_3 are the delay times measured in node B in the first and second round trip respectively (see Fig. 2). This double-sided measurement zeros out the errors of the first order due to clock drift [17].

IV. Network Architecture and Protocol Design

The protocol supports communication and localization in real-time. Owing to this requirement, the medium-access is divided into different time slots (TDMA). In order to provide real-time communication for a large number of AGVs the whole working area is divided into three cells which use different frequencies (FDMA).

A. Network Architecture

Fig. 3 shows the architecture of the whole system. AGVs

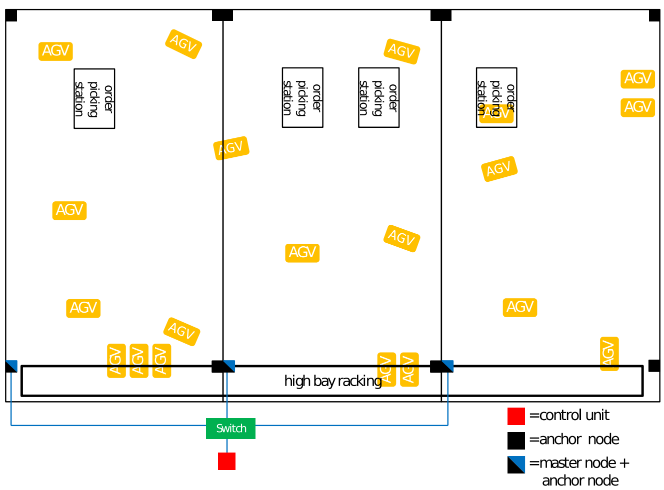

Fig. 3. Wireless network with three cells and router

transport Euro-bins containing one sort of goods from a high bay racking to order picking stations and back to the racking. Order pickers collect the orders from Euro-bins and pack them into custom bins. In order to navigate from high bay racking to order picking stations AGVs localize itself using IEEE 802.15.4a ranging to at least three anchor nodes. IEEE 802.15.4a range measurements are not precise enough to allow docking maneuvers at order picking stations. For docking maneuvers the range measurements are fused with measurements obtained from a safety laser range finder in a Monte Carlo Particle Filter [19].

Every cell consists of a master node and three anchor nodes. The master node controls the medium-access in its cell and acts also as anchor node. Master nodes are connected to a distributed system (Ethernet) for routing purposes. Routing is executed by a central control unit which is connected to the warehouse management system. The control unit stores a routing table with all AGVs connected to a cell. The warehouse management system sends transport orders to the AGVs and monitors their state.

B. Protocol Design

The network protocol supports different services:

- *Ranging*: Every mobile node in a cell (AGV) uses this service to obtain range measurements to any other node in the cell. Usually a mobile node executes ranging to the master node and three anchor nodes during its time slot. To optimize localization accuracy mobile nodes can execute ranging to AGVs at fixed positions e.g. docking stations.
- *Data Transmission*: Nodes are addressed with 16 Bit addresses (8 Bit type, 8 Bit ID), where mobile nodes own the same type. Every node can send messages to other nodes during its time slot. Messages to nodes in a different cell are routed through the master node of the source cell via the control unit and the master node of the destination cell to the target node.
- *Time Slot Request, Release*: Before executing other services, a mobile node has to assign to a cell and request a time slot. After service, a mobile node releases its time slot.
- *Handover*: During their way from the racking to the picking stations, AGVs can travel through different cells. The mobile nodes execute a handover to change a cell, after their position has moved to another cell. Handover is triggered through the position of a mobile node and requested by the mobile node.

The master node controls the medium-access in its cell and send a time slot table in regular intervals as a broadcast. The time slot table contains a time slot for any connected node together with free time slots for concurrent medium-access (CDMA/CA). Fig. 4 shows the format of the superframe together with a time slot table. Every node which is in range

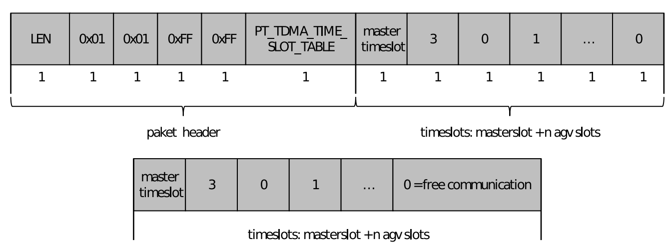

Fig. 4. Time slot table and superframe design

of a cell receives the time slot table and synchronized its real-time clock. The time slot table includes occupied slots and slots for free communication (CDMA/CA). The first time slot in a superframe is always occupied by the master node. The time slots are marked with the address of the nodes (8 Bit ID), free slots are marked with 0. Since all nodes receive the time slot table, they know every node connected to the cell and can transmit data during their time slot directly.

When a mobile node needs to connect to a cell, it waits for the master slot table and sends a request in the first free slot. Media access in free slots are controlled by CDMA/CA. The last slot at the end of the superframe is never allocated by the master node and therefore always free. Fig. 5 shows a sequence chart with a time slot allocation. At the beginning of the first superframe, the master node broadcasts a time slot table, in which mobile node Slave1 occupies the first time slot and Slave2 occupies the second time slot. Slave3 sends a time slot request in the first free slot (Slot3). At the beginning of the next superframe, the master node broadcasts a new time

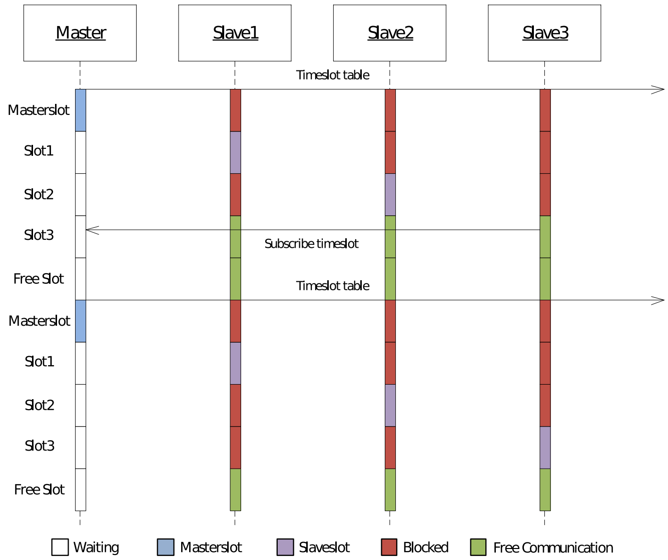

Fig. 5. Allocation of time slot

slot table, in which Slave3 occupies Slot3.

When an AGV travels from one cell to another cell, it must change the frequency and request a time slot in the new cell. The protocol supports this procedure with a handover service. The handover service is requested by the mobile node and triggered by its position. Fig. 6 shows a sequence chart of the handover procedure. AGV requests a handover from Cell1 to Cell2. It sends a handover request to the master node of Cell1. The master node of Cell1 sends a handover time slot request via distributed system and control unit (router) to the master node of Cell2. The master node of Cell2 confirms the handover time slot request with a message to master node of Cell1 which confirms it to the AGV. The mobile node on the AGV change its frequency and waits for the start of the superframe in Cell2 and the time slot table. In its time slot it sends a handover done message to the master node of Cell2, which sends a handover delete message to the master node of Cell1. The master node of Cell1 releases the time slot of the AGV. Master node of Cell2 send a message to the control unit (router), to update the routing table. After this last update the handover procedure is completed.

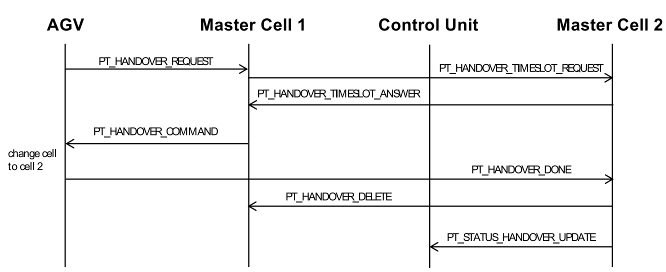

Fig. 6. Sequence chart of handover procedure

Since the assignment to a cell depends on the position of the mobile node, a mobile node has to localize itself, before requesting a time slot in a cell. During initialization of a mobile node its position is unknown. Fig. 7 shows a sequence chart of the initialization procedure of a mobile node and the assignment to the correct cell. In the first step a mobile node changes its frequency to the Cell1. It waits for a free time slot and executes ranging to the master node of Cell1. If the obtained range to this master node is smaller than the width of Cell1 it determines Cell1 as the correct cell. If not, the mobile node changes its frequency to the Cell2 and executes ranging to the master node of Cell2. After that step, the mobile node can localize itself with bilateration and consequently assign to the correct cell.

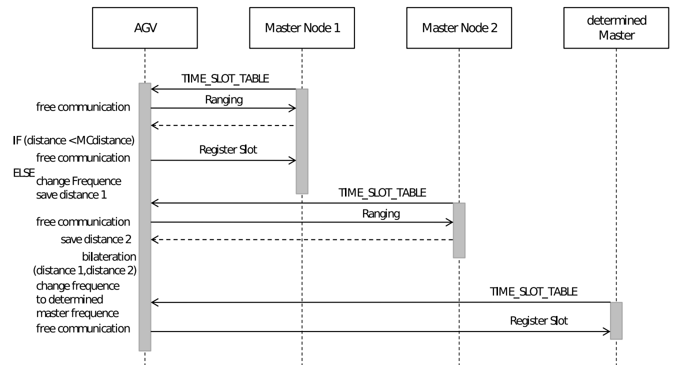

Fig. 7. Initialisation and cell assignment

V. Implementation and Experimental Results

The protocol is designed for a distribution center with 50 AGVs and three cells. In the first step, a system with two cells and two mobile nodes is implemented and tested.

A. Hardware

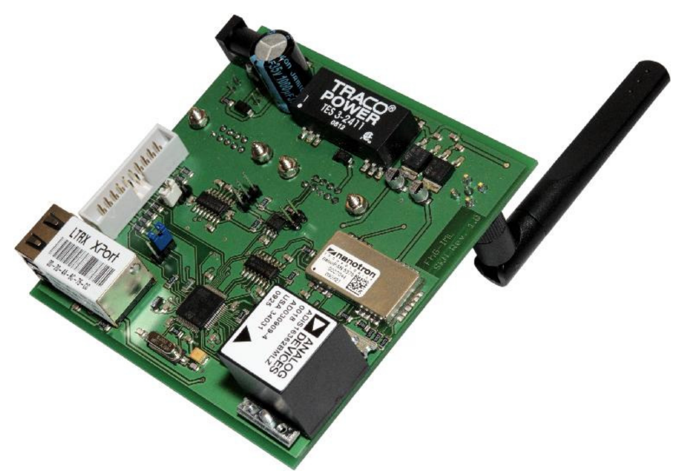

Fig. 8. Wireless sensor node for anchors and mobile tags

In order to fulfill the requirements of the target application, a wireless sensor board was developed that can be used as:

- Mobile node (tag) on an AGV,
- Fixed anchor node,
- Master node with connection to the distributed system.

The board is designed around a STM32 micro-controller which includes an ARM Cortex-M3 core. The STM32 micro-controller provides interfaces and enough RAM and computational power to perform the communication task in real-time. IEEE 802.15.4a radio is built with a nanoPAN 5375 module which supports up to 20 dBm output power and three frequency channels with 22 MHz bandwidth.

The architecture of the wireless sensor board is modular, only necessary components are assembled. Master nodes are equipped with a Xport to connect to an Ethernet. Mobile nodes are equipped with an IMU (inertial measurement unit) which increases localization accuracy of the AGVs. Mobile nodes are connected via CAN-bus to the AGV's PLC (programmable logic controller). Communication to the PLC is performed with CANopen protocol. As a fall back, the boards are equipped with a serial interface (RS-232).

B. Experimental results

Several experiments have been conducted, to prove the implementation of the protocol. Fig. 9 shows the result of a synchronization test. In this experiment three nodes monitor their sync signal on a digital output which is measured with an oscilloscope. The master nodes sends the time slot table in regular intervals over air, the anchor nodes in the cell receive the time slot table and synchronize their real-time clocks. The blue line in Fig. 9 shows the beginning of the master time slot on the master node. The green and red curve show the master time slot on two different anchor nodes. The experiment show, that the delay is less than 0.2 ms which is tolerable for the target application.

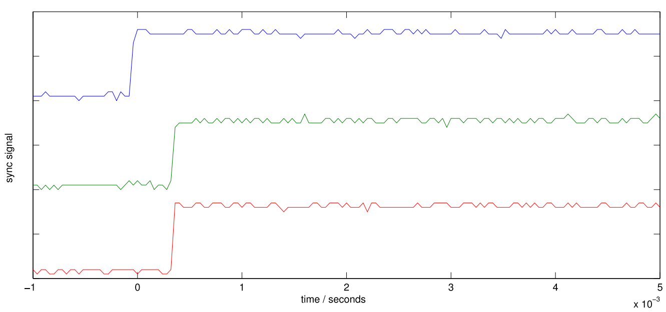

Fig. 9. Wireless synchronisation

VI. Conclusions and Future Works

In this paper real-time communication and localization using IEEE 802.15.4a CSS was proposed. A wireless network and a communication protocol was developed, implemented and tested. The network uses FDMA to divide the area into cells, TDMA for real-time communication and localization within a cell and CDMA/CA for cell assignment and management services. A sensor node was developed which provides all functions to act as a mobile node as well as as a anchor or a master node.

The next step the system will be implemented in a demonstration center with 50 AGVs and three cells.

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