Sensor/Actuator Networks in Smart Homes for Supporting Elderly and Handicapped People

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Abstract—**Smart Home, this term comprises various approaches, engaged in living and working now and in the future. The objectives of the various approaches range from enhancing comfort in daily life to enabling a more independent life for elderly and handicapped people. The term *Ubiquitous Computing*, coined by Mark Weiser describes the ubiquity of computer and information technology. The task of *Smart Objects*, implanted into everyday items, is to sense the immediate environment using various types of sensors, and to process these information. This functionality assigns a kind of artificial intelligence to common, well known objects and enables comprehensive information-processing and interconnection of almost any kind of everyday object. The (preferably) transparent and hidden technology ranges from *Wearable Computers* and *Smart Clothes* to "intelligent" artificial replacements. It supports the user in almost every part of his life by extending his cognition and information processing capacity and tries to compensate for certain handicaps. The challenge regarding smart homes, especially for supporting the elderly and handicapped, is to compensate for handicaps and support the individual in order to give them a more independent life for as long as possible. In this paper, a common architecture for smart home environments is developed, mapped to an experimental setup, and finally evaluated.**

I. INTRODUCTION

Sensor/actuator networks (SANETs) consist of sensor and actuator nodes – usually communicating using wireless technology – that perform distributed sensing and actuation tasks. In recent years, the needs and interest in the capabilities of SANETs has increased. Obviously, SANETs are heterogeneous networks having widely differing sensor and actuator node characteristics [1]. The basic idea is that sensor nodes provide an communication infrastructure while gathering and distributing information about the physical environment [2]. They can, in a certain way, also be used for localization and navigation issues as is partially shown in [3] and will be the subject of future research. Whereas actuators are meant to take decisions based on information from the distributed sensor nodes or local systems. For example, they can offer management and maintenance services, such as repair tasks or energy refreshment to the sensor network. In addition actuator nodes are supposed to provide mobility, e.g. with mobile sensors and so to improve the network through controlled mobility. In many cases, more powerful actuators, such as mobile robots, are used to satisfy the needs of more complex tasks. These robots are autonomous, automatic machines that are capable of movement in a given environment. Probably, the most common class of robots are the wheeled robots. They can take a variety of different tasks as already mentioned to improve and support the sensor network.

The term smart home covers a variety of practical and theoretical approaches dealing with ideas of life, living and working today and in the future [4]. One task is to automate and solve everyday life problems in different areas such as home entertainment and health care and to integrate these single solutions into an overall network. With increasing progress in technology the possibilities for concepts using more artificial intelligence instead of control mechanisms increased. In past years several approaches were presented, each of them offering a single solution. So no date can be named for the first and original smart home. A small selection of relevant and well known projects with different aspects is:

- LIVEfutura (Fraunhofer Institutes) [5]
- Futurelife (Huenenberg/Zug, Beisheim Group Metro) [6]
- OnStar at Home (Detroit, Internet Home Alliance) [7]
- TRON Intelligent House (Nishi Azabu, K. Sakamura) [8]
- Smart Medical Home Research Laboratory (University of Rochester) [9]
- INGA (Innovations network building automation) [10]

In the next step, research will head for artificial intelligence, self-learning, and self-organizing systems. The environment represented by intelligent objects is no longer managed by a central control. It is gathering and analyzing data while working almost autonomously. So it is possible to identify (behavior-) patterns in all sections of our life, like consumption, sleeping, etc. The user must not feel reliant on technology, or watched and controlled, which requires transparent technology and hidden complexity, especially in respect to the wide range of different users.

The focus of this paper is on helping elderly or handicapped people to live a more independent life as long as possible. Those people are an important target group concerning smart home environments, so special requirements have to be taken into account. For example a health monitoring and emergency help system has to be established. The requirements made to control infrastructure and interfaces have to be easy and self-explanatory. The user should be integrated and feeling well in the new environment. When developing smart home environments for this target group the main focus is on compensating handicaps and limitations. In our work, we established and tested a SANET in a realistic environment in order to assume certain tasks, such as monitoring and control of domestic systems, home entertainment, and health care. Based on the collected data, a central diagnosis center or station is able to analyze and monitor the patient's behavior. For example, unused active systems like lights can be identified, analyzed, and controlled. For health care applications the collected data can be correlated. Concerning the sensor network, the operation is subject to certain technical constraints. So the sensor nodes are only conditionally reliable. Furthermore, new functionality for maintenance, management, and diagnosis ought to be integrated. Thus, the deployment of mobile robots seems to be a well suited approach. They may validate certain data measured by sensor nodes, allocate tasks, reprogram sensor nodes, and localize frequently lost objects (FLOs) such as keys and several other cooperative task. In addition, the mobile robots can be used as base stations for the smart home environment. Our work comprises to set up a test scenario showing the mentioned functionality in smart homes.

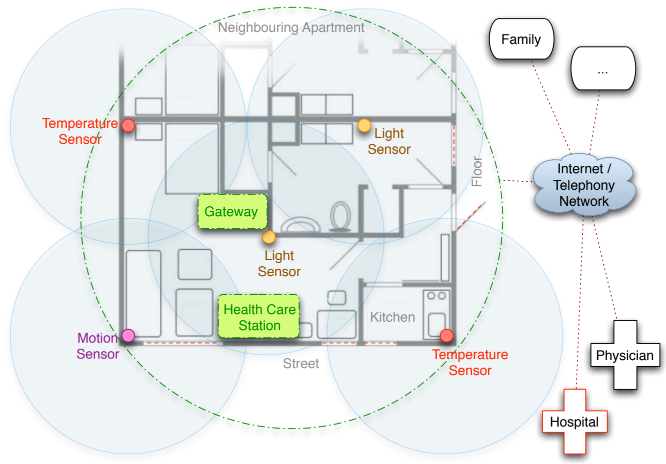

Fig. 1. Overview - A Common System Architecture

II. Our Smart Home Scenario

In this section, a possible application scenario for smart homes is introduced, assuming a usual apartment owned and inhabited by an elderly person. The subject may be handicapped in several ways, as senses and capacity to remember are not so good anymore. Also the person is not able to see the physician anytime he needs or wants to, because of the fact that he is unable to make his way to the physician's practice. Hence a solution must be developed which enables the patient to talk to his physician in a comfortable way. The physician must have the possibility to remote-view vital signs and values and to interact with the patient, as if being in a normal practice. Additionally the family members may be spread over the whole world living hundreds or thousands of kilometers away. Often there are not even any caregivers in the neighborhood. Thus, in case of an emergency, a reliable emergency system must call the physician and the ambulance and notify the immediate family about the incident.

A. Objectives

Of particular concern to an elderly or handicapped person, the higher-level goal is to compensate any limitations in any part of his life as far as possible, to enable the patient to live a more independent life as long as possible. Now keeping the global task in mind, it is possible to list a basic set of objectives for a smart home scenario. So the first objective to be named is the development of a sensing and monitoring system, which takes over the part of the named subject's wasting senses and if necessary maintaining his capacity to remember. In detail, the architecture must take care of domestic systems, air condition, lights, and heating as well as control the basic functions of home entertainment and security systems. To Interact with the physician and to get the vital signs and values checked keeping the physician up to date, as an additional goal, the architecture must be developed to gather data, analyze data locally, make data accessible, initiate an emergency call, and provide video/audio communication. Additionally, mobile robots should be used for maintenance and management tasks concerning the network, global task allocation, as mobile sensors, and for localizing frequently lost objects (FLOs).

These objectives require a remarkable amount of technology to be used. But the fact that this technology must be transparent and easy to use, is one of the most important points. All improvements and technology are useless if they are not accepted by the user. Thus, the user-system interface must be as simple and powerful as possible. And the system must basically operate in a self-organized way.

B. Common System Architecture

In the following section a common system architecture based on the given objectives, is developed. In order to show the evolving possibilities in smart home environments, certain existing constraints are sometimes disregarded. In figure 1 an overview for a common system architecture, especially referring to the needs of elderly and handicapped people, is depicted. The central point of interest, in our case, is an apartment, which should be changed into a smart home. Therefore, the apartment is equipped with several technological systems. These systems have to be interconnected supporting the user in a transparent way, as far as possible. Wireless network technology should be used to link various well known concepts, such as security or home entertainment systems, as well as so called smart objects. These smart objects are common objects with small integrated microprocessors communicating via wireless networks. They are typically equipped with various sensors to observe the environment and it is possible to use them as actuators, as well. Smart objects are usually mentioned in conjunction with the idea of ubiquitous computing, which characterizes the omnipresent information and computer technology implanted into everyday items. But also the immediate and distant surroundings, covering neighbors, physicians or hospitals, and the family, existing networks and technology, as the Internet, the public telephony network, and home automation systems must be integrated into the idea of a smart home environment.

A wireless sensor/actuator network, sometimes using the mentioned smart objects, provides the possibilities to control various systems in a self-organized and self-learning way. In terms of economy, common processes, concerning domestic systems, air conditioning, light, and heating, may be optimized making them work together in a more intelligent way. One well known technique is to use sensors and actuators to set up feedback loops. So sensors and actuators may provide functionality based on predefined rules as well as behavior evolved from a learning process. The environment is thus controlled in a self-organized way. In order to give a few examples, the heating can be controlled economically as well as the light and the air conditioning. Furthermore the fridge may keep a list of the contents to automatically order depleted foods directly from the supermarket, which are then delivered to the apartment. Also intelligent carpets, using RFID technology could be part of a security system. However they may be part of a surveillance systems to ensure that the patient is still alive, capturing motion and other behavior patterns as well.

Besides normal or implanted sensors or sensor plasters wearable computers and other smart objects may be used to keep an eye on the patient while he lives in a common environment. If possible, neighbors may be involved for immediate help, too. An emergency system may directly notify the neighbors, without additional costs, using a Bluetooth enabled device, in case of unusual vital signs. A reliable emergency system must also notify the physician and the hospital in case of an emergency. For these purposes existing networks, like the Internet or the telephony network, may be used. The system can rely on several kinds of third party mechanisms. A pager or mobile device may be called over the public telephony network or a directly connected emergency notification system may be used via the Internet, which depends on the given interfaces provided by existing emergency notification systems.

Obviously, the various heterogeneous networks must be merged. Therefore, one or more gateways between the networks are needed. The sensor network may communicate using Bluetooth technology while the rest of the systems are WLAN enabled. As it is possible to provide more than one gateway, the first one may connect the Bluetooth sensor network to the internal WLAN while the second one handles incoming and outgoing calls as well as Internet services. Mobile robots are another helpful extension to the smart home environment, as they are able to provide a variety of services. The mentioned gateway functionality, between the sensor network and the WLAN, can be covered by a mobile robot, for example. On one hand they may be used to support, and maintain the network to encourage the reliability of the network and on the other hand, to observe the environment and the inhabitants, while locating frequently lost objects (FLOs).

C. *Real-life requirements and lab limitations*

In order to map the developed architecture to a realistic representation, certain requirements are applied to the components and assemblies as well as to the environment and the user. The mapping must incorporate the given budget and possibilities. All devices must provide the necessary interfaces to be interconnected in the overall network. Although their design has to be aligned with their pre-determined domain. In apartments and family houses, the requirements differ to those of office and factory buildings. Small and nicely built devices are necessary for a certain comfort. The possibility for a high-speed Internet connection is required to satisfy the needs for several services, like audio/video telephony and interactive medical care. With the research in (W)BAN systems going on very quickly, the possibilities are improved and so versatile and more exciting technology will be affordable and in a certain way invisible in the near future, like for example sensor plasters or implants. Up to now, the technical units and devices commonly used in (W)BANs may be interfere with normal life sometimes, being present, visible and tangible all the time. Requirements are also made to the environment and the user, as if the apartment is considered to be suitable to set up a sensor network either wired or wireless. In order to deploy mobile robots the flooring has to be adapted, too. The users must be willing to use and understand the technology on a certain lower level to handle it, even if efforts are made to simplify processes and usability as far as possible.

For developing a demo scenario in our lab, several limitations have been identified for using the existing hard- and software as a basis to implement a smart home test environment, which maps the designed common architecture. Obviously, the environment is limited or rather simplified in certain terms. In contrast to an apartment or family house the laboratory is furnished with some chairs, tables, and experimental setups. Additionally, workstations and other technical equipment are arranged. So the concept of a usual living space must be abstracted. Within the budget it is not possible to set up an environment with all named devices, like domestic, home entertainment, security system, and air conditioning. The dedicated server provides proxy and web services. Within the available hardware, no components to implement a BAN are included. The used RFID reader offers a maximum reading distance of 10cm, what implies that the RFID tags ought to be placed on the ground. They should also be placed in a way so as not to interfere the robot's movement. Concerning these facts, the architecture has to be generalized and in a certain way simplified to get an abstraction for experimental purposes.

III. Implementation

As the test scenario was to be set up in our laboratory, the architecture's mapping specified has to be within the boundaries of possibility. In our lab, several BTnode sensor nodes and mobile robots called Robertino are available. With the available implementations and basic technology from prior work, considering the limitations pointed out in one of the following sections, the architecture is mapped to an experimental setup as it is depicted in figure 2, which represents the research environment. It may be roughly divided into the following sub-networks: Bluetooth, Wireless LAN, Radio Frequency ID (RFID), Internet (TCP/IP), and the telephone network.

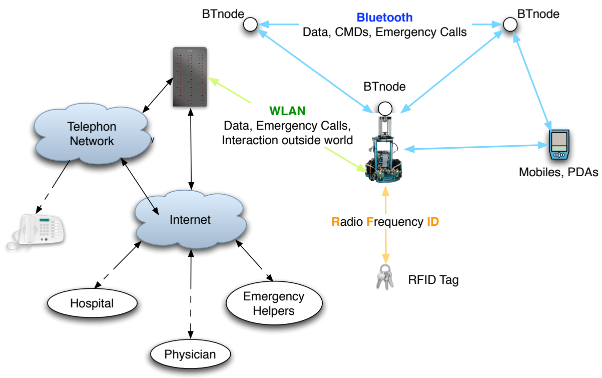

Fig. 2. Architecture for the lab setup

With regard to the architecture a sensor network is mentioned to interconnect the deployed BTnodes and to diffuse sensor data values over the network, which is implemented by a Bluetooth network. A private WLAN has already been installed in the laboratory using a wireless access point. So it possible to access the mobile robot system from a workstation or another systems within the network. The access point is connected to the Internet and to the university network. A gateway has been set up in terms of a dedicated server, which is used for several purposes by the ROSES project. It provides an Internet connection via the university network and a web service. The RFID system is not a network in the common sense but it provides the possibility to transmit data from the RFID tags to the RFID reader.

A. Sensor Network

The sensor network is based on BTnodes interconnected via a common Bluetooth network. On top of the L2CAP layer, a multi-hop protocol has also been implemented by the BTnut API. Within a multi-hop protocol it is possible to send messages to sensor nodes, even if they are not directly connected to each other. That fact eases the problem of covering the whole laboratory or the living space of a smart home with the desired sensor network, respectively. This means that sensor nodes can be placed wherever there is the greatest need. So the problems of either wired solutions and even the constraints, concerning common Bluetooth communication ranges, are solved. In addition, using Bluetooth to set up the sensor network affords to integrate Bluetooth enabled mobile devices.

As the BTnodes ought to operate as sensor and actuator nodes, a sensor may be connected to one of the I/O lines provided by the BTnodes. Two possible ways exist to connect sensors or sensor boards to the I/O lines using either the connector on the usbprog rev2 board (see figure 3 (b)) or a direct connection using two other connectors, placed on the BTnode itself (see figure 3 (a),(c)). The sensors may be plugged directly to the connector pins. Here a light sensor called TSL252R is used. In the first approach, the sensor has been installed on a simple sensor board, in order to develop

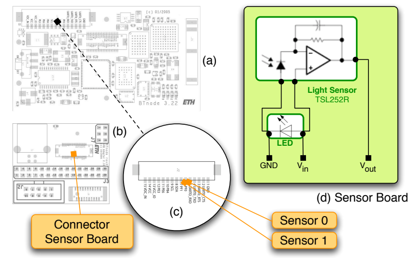

Fig. 3. BTnode Connectors Assembly - Sensor Board Circuit Diagram

a proper and reliable but simple solution. In figure 3 (d) the circuit diagram is shown.

In terms of the smart home sensor network, a simple protocol, set on top of the MHOP protocol layer, has been developed. It comprises three types of messages, which are divided into subtypes according to the needs. So the different message types may be handled with different priorities, if necessary. The main message types and their sub-divisions are shown in figure 4. If any uncommon parameter is recognized in the sensor network covering the environment, the BTnode, which detected the anomaly, initiates a broadcast *emergency call* to diffuse the information. So any device integrated into the Bluetooth sensor network is able to react in an appropriate manner, if it is using the same protocol. The emergency call messages are split into *light sensor messages*, *temperature sensor messages*, and *motion sensor messages* with the option to be extended. Here, only light, temperature and motion sensors are available, so the given sub-division satisfies the demands.

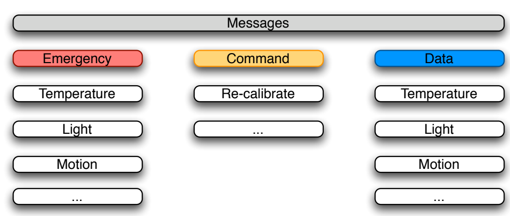

Fig. 4. Smart Home Protocol - Message Types

An appropriate response to an emergency call, initiated by a light sensor, would be to switch on/off the light. Concerning the experimental setup, the actuator activity is simulated by a buzzer sound. If the initiator does not receive an acknowledgment within a certain time limit, it repeats to send the emergency call message. This continues until an actuator confirms the initiated emergency call with an acknowledgment, after finishing the action. In both directions broadcast messages are used because an acknowledgment from one of the nodes ought to stop the reactions on other nodes or the mobile robot. So in case of an emergency call the fastest solution wins and stops the others by confirming the request in the first place.

Command calls are initiated to start a remote process on a sensor node. In this case a command for a re-calibration has been implemented, which simulates a re-calibration process by blinking LEDs, as mentioned above. A command call is acknowledged by the receiving sensor node, as well. In this case a message is addressed to the initiator only because no other devices are involved.

Data calls are messages sent intermittently to maintain a chronicle of the environment status. The gathered data can be analysed or just shown to users in and outside the smart home. The name *call* was chosen, in order to keep uniformity of naming. Actually, it is a simple unacknowledged message.

B. Robertino

The basic functionality is given, in terms of the development framework Robrain[1] and several plug-ins, e.g. *rfidReader, PathFinder, SerialDevice, vdcUnit*. The *smarthome* plug-in merges the offered solutions to implement a behavior plug-in, which defines the mobile robot's behavior within the smart home scenario. The Robertino has to be integrated into the sensor network and must be able to locate FLOs by passing them on its way, somewhere in the designed experimental environment. In order to integrate the mobile robot into the sensor network a BTnode is used, which is connected to a common USB port. It is possible to verify values measured by sensor nodes using the BTnode on top of the robot and the appropriate sensors. With the camera device, pictures and small video sequences can be stored for multiple purposes. Additionally, the Robertino embodies a base station for the sensor network and interface between the gateway, which represents the outside world, and the sensor network.

With regard to the sensor network, the mobile robot ought to be responsible for maintenance and management tasks concerning validation and substitution as well as re-calibration of sensor nodes and data storage. So, if the robot notices multiple unacknowledged emergency calls, it checks the sensor node. If a sensor node shows a suspicious behavior, the mobile robot instructs the BTnode to re-calibrate by initiating a command call. In either case the Robertino takes a picture of the current situation and notifies the next level instance - the user - via Bluetooth SMS messages or using the Internet connection, if no Bluetooth enabled mobile device is available.

The robot ought to observe the laboratory on predefined paths. In order to manage the sensor network and observe the environment, the robot's navigation within the environment has to be laid out to locate certain coordinates within the environment. Therefore the *PathFinder* plug-in is used. Regarding the plug-in's abilities, it is predestined to find the optimal path from a given starting point to a certain target. If the robot decides to get in touch with the sensor node based on the above mentioned reasons, the plug-in finds the optimal path referring to an assigned map of the environment.

As no further localization approaches are deployed, the installed BTnodes must be marked on the environmental map. Therefore, a table of the installed BTnodes is set up in order to assign a sensor node's address with an area on the map.

[1] see http://robrain.berlios.de/

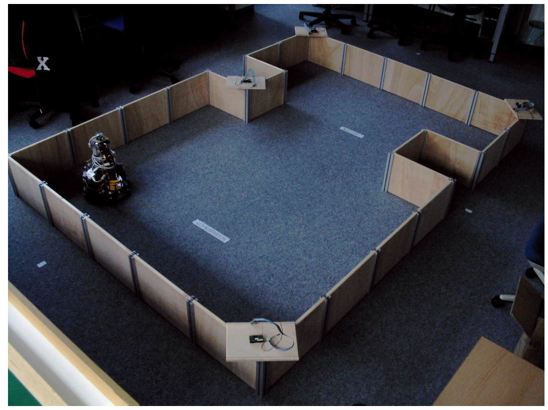

Fig. 5. Experimental Setup

Additionally, the mobile robot may now use the dynamic mode offered by the *PathFinder* plug-in to update the given map. While crossing the room on a predefined path the robot is able to locate FLOs using the RFID reader system installed on the Robertino. If an FLO is found the object's ID is assigned to the current position, in terms of coordinates on the map used in the *PathFinder* plug-in.

C. Gateway / Mobiles

The gateway is the bridge between the in-home network and the outside world. An apache web server is used to make data, gathered by the sensor network and stored by the Robertino, available from outside the smart home. Following the architecture's design, an approach for audio/video calls was implemented. Due to the fact that several public and commercial approaches already evolved, it is not necessary to test theses systems. So, such a system is not implemented in our experimental setup. The given approaches are quite well suited to satisfy the requirements, even if improvements, especially in terms of reliability, are desired.

In order to show the possibility of communication between the mobile robot and a mobile device, the Robertino ought to be able to send SMS messages to a mobile phone. In our approach, messages are transmitted via Bluetooth using the available Bluetooth module on the BTnodes. So, no further hardware is required and additionally no further costs arise.

IV. Demonstration

A demonstration, which is described in this section, was performed to test and to evaluate the presented architecture. The demonstration scenario is set up to show the interaction of the particular solutions. Figure 5 shows a picture of the experimental setup. First, an area has been defined to represent a simple smart home environment. In our case it embodies a small apartment including a living area and a kitchen. The area is framed by surrounding wooden plates. A sensor network connects three BTnodes, each equipped with the BTsense v1.1a sensor boards and according sensors. Each node is configured to use one sensor. So, a light, temperature, and motion sensor node is available. Each sensor node distributes

Fig. 6. Snapshot of the web page

the measured sensor data in time intervals of 30 seconds. The time intervals have been calculated to limit the demo to about 5-10 minutes.

If the sensor values are out of range the nodes initiate emergency calls. A value is out of range, if the light value falls below $300 * 10^{-6}\ W/cm^2$ or exceeds $800 * 10^{-6}\ W/cm^2$, also if the temperature falls below $15\,^{\circ}\mathrm{C}$ or exceeds $35\,^{\circ}\mathrm{C}$, and if the motion sensor did not detect any motion during the last minute. Also, a fourth node is configured to behave as a simple actuator, in order to demonstrate a feedback loop. In our scenario the BTnode acts as a switch if the light value is out of range. This is simulated by a beep sequence using the buzzer on the BTsense sensor board.

The motion sensor is used to show the mobile robots behavior. If the sensor sends more than 5 unacknowledged emergency calls the robot stops observing the living area, acknowledges the call, and moves directly to the node. It takes a picture of the actual situation and sends a SMS message via Bluetooth to a mobile phone. Then the Robertino returns to the position, where it stopped before and continues observing the living area. A dynamic generated web page presents all gathered data and the according plots (see figure 6).

V. Discussion and Conclusion

The increased interest in ubiquitous computing affords a wide spectrum of new small and easy to use technology. The smart objects, sensor nodes, actuators represented by control units or mobile robots and other technologies that are meant to be little helpers in nearly every part of our life have become more and more available and affordable. With the rapidly increasing research and development progresses taken into account, soon these objects will become as common as mobile phones and PDAs in this time. Concerning health care, it becomes possible to observe and advise patients while living in their familiar environment, instead of spending months or even years in hospital. Medical and senior care becomes easier and more secure in case of an emergency, because immediate help is available.

The experimental setup represents a good approach to research smart home environments, keeping in mind that many things have been abstracted to a certain extent and a few problems are still waiting to become solved. Regarding the reliability of the developed systems interacting within a smart home scenario, certain weaknesses have been observed, although the various parts are working very well on their own and also in combination with other systems. Another problem with respect to the system's reliability concerns the connectionless Bluetooth multi-hop network, as it is not providing any transport layer mechanisms for reliable data transmission.

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