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Wireless ad-hoc control networks

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Abstract

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Wireless ad-hoc Control Networks

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Index Terms – control network, service discovery, IEEE1451

I. INTRODUCTION & BACKGROUND

The advances made in computer networking have had significant impact on industrial controllers. These control systems were traditionally central and hierarchical where large centrally located mini-computers were connected directly to dumb I/O racks through the I/O ports of the computer. The first major change took place when a distributed architecture was adopted. In this configuration, a central computer supervised distributed direct digital controllers (DDC) with some local intelligence in the I/O modules, which has been widely deployed nowadays in the industry. The latest development in DDCs is NET+ARM [1] which is an Ethernet-ready System on Chip (SOC) providing an ideal platform for developing a network-enabled real-time application.

In the 1980's, network connectivity was introduced between the supervisory computer system and DDC through dial up link. The supervisory computer ran the proprietary vendor software. The dial up connection was replaced by Ethernet in the early 90's and various control modules in the DDC were linked up by vendor propriety networks. Around 1995, the proprietary software running on the supervisory control was replaced by browser-based front end. Many industrial networks have also been developed by various standard organizations to satisfy the real-time requirements.

LONworks [2] technology developed by ECHELON Co. has been widely used in industrial and home automation. LONworks is a control network technology which uses a control network protocol called LonTalk, and also known as the ANSI/ EIA 709.1 control networking standard. LonTalk is different from a TCP/IP network. Accordingly, LONworks does not support IP networking. Shahnasser and Wang [3] managed to establish some interoperability between LONTalk and TCP/IP and have demonstrated that it is possible to control various devices over TCP/IP and LONTalk.

Since the beginning of the year 2000, IEC 61158 fieldbus standard with eight protocols including Profibus, Fieldbus Foundation and WorldFIP has been announced as an international standard to end the fieldbus war [4]. However, the IEC 61158 has the great disadvantage that it still keeps a diversity of eight different solutions [5].

In recent years, Ethernet [6] has become increasingly popular in automation due to its low cost, availability, flexibility, and high communication rates. Ethernet is not created to guarantee the delivery of time-critical information and thus presents disadvantages when used as a control network. With the introduction of switched Ethernet and certain modifications of the protocols, however, these problems have been alleviated.

With the advent of mobile computing and wireless communication, ad-hoc distributed systems are becoming feasible and attractive. Such systems represent peer to peer wireless communication among intelligent devices without any fixed infrastructure. The peers form a network of various devices including sensors, actuators, appliances, PDAs, laptops, etc.

A new concept called Wireless ad-hoc Control Networks (WACNets), designed for distributed and remote monitoring and control is explored in this work. Such systems represent the next stage in the evolution of distributed control and monitoring. Recent advances in mobile computing, wireless communications, MEMS-based sensor technology, low-powered analogue and digital electronics, and low-power RF design have created opportunities for the introduction of WACNets.

WACNet explores a framework for organic, evolutionary and scalable method of integrating a large number of intelligent and heterogeneous nodes. Each node consists of sensing and/or actuation, local intelligence and control, data processing and communication components. The size, number, density, capabilities and location-dependency of such nodes will be determined by the specific application for which the nodes are employed. Ideally they are expected to be low-cost, low-power, multi-functional and small in size.

The protocols and algorithms that run on the nodes could also provide self-organizing and cooperative capabilities for random deployment of the nodes. This implies that a node has ability to change its behavior based on external/internal stimuli. This is achieved with no skilled human intervention. Each node contains sufficient intelligence to make local decisions based on global or regional system state. The synergy of all the local decisions and actions represent the overall system process.

WACNets have potential for employment in a variety of applications including environmental control of large buildings complexes, smart home control for security, identification and personalization, robot control and guidance in automatic manufacturing systems, and interactive toys. In addition, WACNet can be employed in distributed control, information dissemination, in-network

processing and other distributed computations such as sensor fusion, classification, and collaborative target tracking [7]. They can have direct applications in commercial, industrial, agriculture, health and defense sectors. There are also possible applications in personal and institutional security, radiology, and medicine. A typical WACNet for building services is illustrated in Fig. 1.

The proposed system offers new capabilities not present in the currently available industrial control systems. These new capabilities include:

- True ad-hoc structure, which simplifies the design, maintenance, extensibility, and scalability of the system.
- True peer-to-peer communication with no central supervisor, which introduces unnecessary overhead and complexity.
- Cost effective scalability.
- Cost effective wireless communications, which will significantly reduce the cost of commissioning and control of a control system.
- Provision of an evolutionary system through its ability to reconfigure in an autonomous fashion and provide an optimal distribution of resources.
- Robustness with respect to both disturbances and uncertainties.
- Interoperability in heterogeneous system environments.
- Verifiability of the system features at various levels of computational complexity.

This paper provides an overview of the WACNet concept and the approach pursued to realize it. It is organized into six sections including the introduction. Section Π provides a general overview of WACNets. Section Ш presents the evolution of WACNets. Section IV focuses on the design of WACNets. Section V specifically describes service discovery and Service Discovery Protocol (SDP) in WACNets. Section VI summarizes this paper, and outlines future work possible.

Π. SYSTEM OVERVIEW

A WACNet consists of a set of geographically distributed intelligent and heterogeneous nodes. Each node consists of a processing unit, wireless communication unit, and transducer ports which can connect to one or more sensors
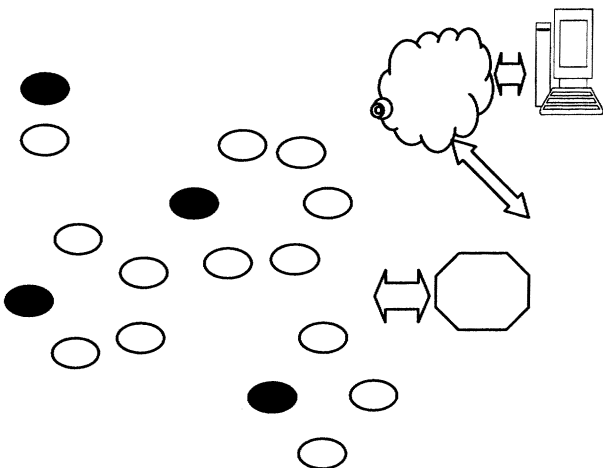
or/and actuators. The processing unit can perform signal processing and control depending on the services required from the node and the type and the number of sensors/actuators attached to it.

Each node contains sufficient intelligence to make local decisions based on global/regional system state, and has ability to change its behavior based on external/ internal stimuli. A collection of nodes up to eight which are dedicated to achieve a particular task is called a cluster. A set of clusters working together towards a common objective forms a network. The membership of the clusters and the configuration of the network can change dynamically as the overall system evolves or some nodes fail. The network is ad-hoc as there is no network infrastructure or central administration.

In the proposed system, IEEE 1451 standards are employed because of their ability to provide self-identification, self-testing and adaptive calibration [8]. A combination of IEEE 1451 compliant smart sensor and Bluetooth standard implements several advanced features such as plug-n-play while maintaining minimum hardware overhead at the transducer nodes. The combining model is illustrated in Fig. 2.

XDCR: Transducer (Sensor – Actuator)
STIM: Smart XDCR interface module
NCAP: Network capable application
TII: XDCR Independent Interface
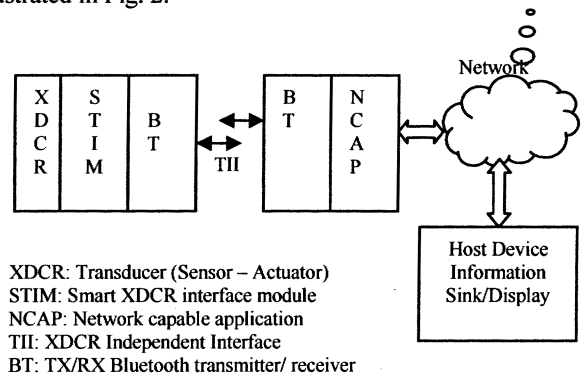BT: TX/RX Bluetooth transmitter/ receiver

Fig. 2. The Combining Model of IEEE 1451 and Bluetooth Standard

As illustrated, a STIM communicates with an NCAP module over a Bluetooth link. The TII protocol, which defines a form of communication between the STIM and NCAP, is implemented via Bluetooth. NCAP nodes are connected to the local monitor and /or control system. An operator can monitor or control the whole system in real time through the local monitor system on demand. The network model of WACNet is described in Fig. 3.
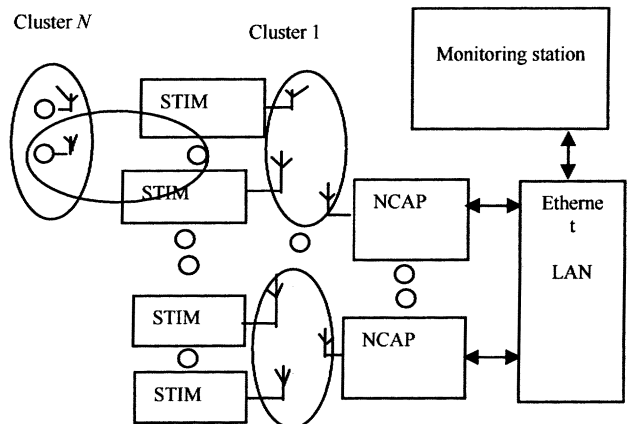

Fig. 1. A typical WACNet in a building

Fig. 3. The whole network model of WACNets

III. EVOLUTION OF WACNET

A WACNet goes through different stages of operation during its lifetime:

(a) Boot up: In this phase, the nodes are initialized and when ready, are placed in a listening mode. In this mode, the node listens for other devices and builds an identity list of devices within range. Once the node has identified and listed all of the other nodes within its communication range, it is then ready to move to the next phase.

(b) Service Discovery: During this period, the nodes advertise the services they can offer including the sensing and actuation capabilities. They will also provide information about their information processing capabilities and control strategies that they may offer. This phase could also be referred to as a "capability exchange" procedure.

(c) Cluster formation: Neighboring nodes with common or complimentary functions form clusters of nodes and start to coordinate and synchronize their activities to achieve their common goal. Within a cluster, one node is designated as the master of the cluster and the rest are slaves. The master node coordinates and synchronizes the activities of the cluster. The master will keep a registry of nodes associated with that cluster. The service list offered by each node includes identification of the node as a master.

The task of cluster information can be accelerated if the functions expected from the network are broadcast to all nodes. This information assists the nodes to match their services with the network requirements. This stage represents the first step in self-organization and cooperation. Any node is capable of being a master and will have sufficient resources to perform this role. The registry information that describes the cluster is held by all nodes and not just the master. This adds redundancy to the cluster identity in case the master node drops out for some reason.

(d) Network operation: In this phase all of the clusters in the network operate concurrently. The status of each cluster is hopped through the network to the monitoring station. The transfer of data is performed by having the master of one cluster communicating directly with the master of another cluster. Information is moved across the network using a typical ad-hoc approach. The master node is identified by the role defined for the node in the list of services offered by it.

(e) Network Evolution: As the operation of the network evolves, it might be required to get involved in new tasks. This will result in further self-organization as described in stage (c). Further evolution of the network can take place with the addition of new nodes due to:
- failure of some of the nodes.
- any new requirements of the network, as it enters into new stages of its operation.
- addition of new devices to the environment requiring control and monitoring.

IV. DESIGN OF WACNET

A. Design of the STIM Nodes

IEEE 1451.2 standard defines a smart transducer interface model (STIM), a transducer electronic data sheet (TEDS), and a digital interface to access the data. The schematic structure of the STIM model in IEEE 1451.2 standard is illustrated in Fig. 4 [9].

STIM can perform different functions including local sensing, actuation and control depending on the services required from the nodes, and the type and the number of sensors/actuators attached to it. The functional block diagram of a typical STIM in WACNet is illustrated in Fig.5.
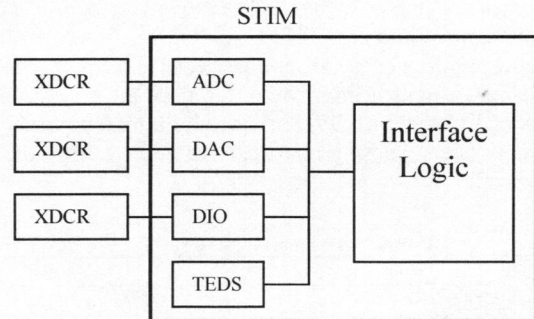

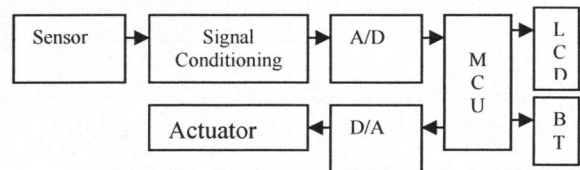Fig. 4. Schematic structure of STIM model

Fig. 5. Architecture of STIM node

In this system, the measured signal from the sensor is amplified, filtered and digitized via an A/D converter. The digitized data is then sent to a microcontroller unit (MCU) for processing. The digital signal produced in the node is converted into analogue before it is sent to drive the actuator. With the deployment of a Bluetooth (BT) wireless device, all data collected in the node can be transmitted wireless to other nodes.

The node in this work is illustrated in Fig. 6. The MCU is PIC16F877 which supports in-circuit programming, and allows user's code to be downloaded into the PIC while it remains on the board. The Bluetooth system is implemented using ROK 101 007 as it provides a reliable full duplex
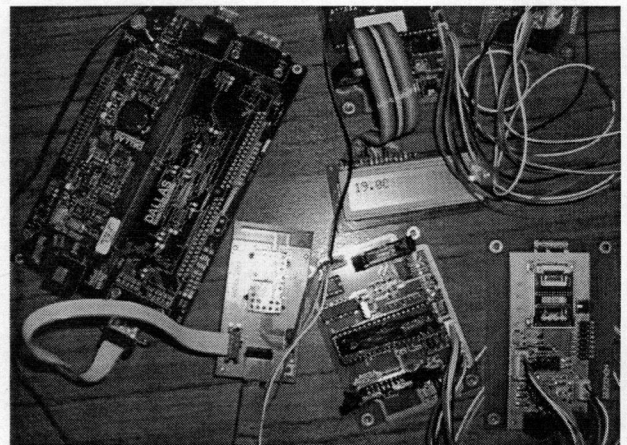

Fig. 6 shows the development board used for the proposed system

communication link, with the ability to form small networks called piconets, compliant with Bluetooth version 1.0B, low power consumption and has a range of 10 meters (0dBm). The golden colored metal cover of ROK provides an excellent RF shedding. It also has a 50 OM antenna interface for the best signal strength performance.

In the proposed system, TEDS uses an object-oriented approach to describe the properties and service abilities of the total STIM unit and transducer channels it controls. The parameters of TEDS have been redefined to meet the requirement of the WACNet and they are stored in a non-volatile memory with each STIM.

In each STIM node, TEDS consists of one meta-TEDS that includes common information for all of the transducers, and several channel-TEDSs that include information about each transducer, whose parameters are defined in Table 1 and Table 2.

Table 1
Parameter definition of Meta-TEDS

Meta TEDS			
Field #	Description	Field Length	Field Type [9]
1	Meta TEDS Length	1 Byte	U8
2	STIM Name	4 Byte	C32
3	STIM ID	6 Byte	U48
4	Maximum Data Rate	6 Byte	U48
5	Number of Implemented Channels	1 Byte	U8

The parameters of this table are defined as follows:

- STIM Name: The name of the STIM defined by the manufacturer.
- STIM ID: Identification field associated with the STIM, whose value is globally unique. In the proposed system, the MAC address of Bluetooth model attached to the STIM can be employed as the STIM ID.
- Maximum Data Rate: Describes the maximum data rate supported by the STIM interface, in bits per second.
- Number of Implemented Channels: The number of transducers attached to the STIM, up to 255. A Channel number of '0' is called CHANNEL_ZERO and addresses all transducer channels within a STIM.

Table 2
Parameter definition of Channel-TEDS

Channel TEDS			
Field #	Description	Field Length	Field Type [9]
1	Channel TEDS Length	1 Byte	U8
2	Transducer Name	8 Byte	C64
3	Device Manufacturer	8 Byte	C64
4	Transducer Status	1 Byte	U8
5	Transducer Priority	1 Byte	U8
6	Group ID	1 Byte	U8
7	Channel Type Key	1 Byte	U8
8	Technical Parameters	N Bytes	-

The parameters of this table are defined as follows:
- Transducer Name: The name of transducer defined by the manufacturer.

- Device Manufacturer: Text string identifying the manufacturer of the transducer unit.
- Transducer Status (TS): Transducer can be read (TS =1) or written (TS=2) or both (TS=3).
- Transducer Priority: The value of priority is decided by the real-time requirement of the transducer. For example, the real time constraint on light sensors is tighter than temperature sensors.
- Group ID: STIM nodes with the channel of same Group ID can work together to implement one particular task.
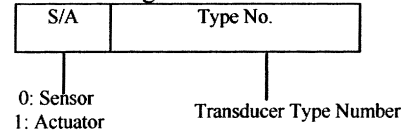- Channel Type Key: It specifies the channel transducer type, as illustrated in Fig. 7.

Fig. 7 Definition of Channel Type Key

00H is defined as general sensor and 80H as general actuator.
- Technical Parameters: The number of parameters and field Length N bytes vary with the transducer type. Technical parameters for a temperature sensor are shown in Table 3.

Table 3
Definition of technical parameter of a temperature sensor

Field #	Description	Field Length	Field Type [9]
8	Technical Parameters	11 Byte	-
Measuring Range			
	Lower Limit	4 Byte	F32
	Upper Limit	4 Byte	F32
Measuring Accuracy			
	Accuracy	3 Byte	F24

B. Design of the NCAP Nodes

The NCAP module is equipped with both Bluetooth and Ethernet physical layer components, in order to provide gateway function for one or more wireless STIM units. Wireless STIM units transport their data to the backbone LAN (on which the monitoring station lies) via the NCAP module. The NCAP module receives data from STIM units via a Bluetooth receiver, transforms these Bluetooth packets to Ethernet packets, and forwards them to the monitoring station.

At this stage, the NCAP is realized by deploying a TINI (The Tiny InterNet Interface) board. In the proposed system, TINI takes on the role of a HyperText Transfer Protocol (HTTP) server and therefore any computer on the network is able to access or control the hardware without the need for extra drivers. The block diagram shown in Fig. 8 illustrates how the hardware devices interact.
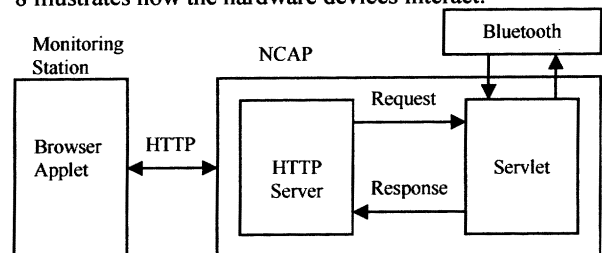

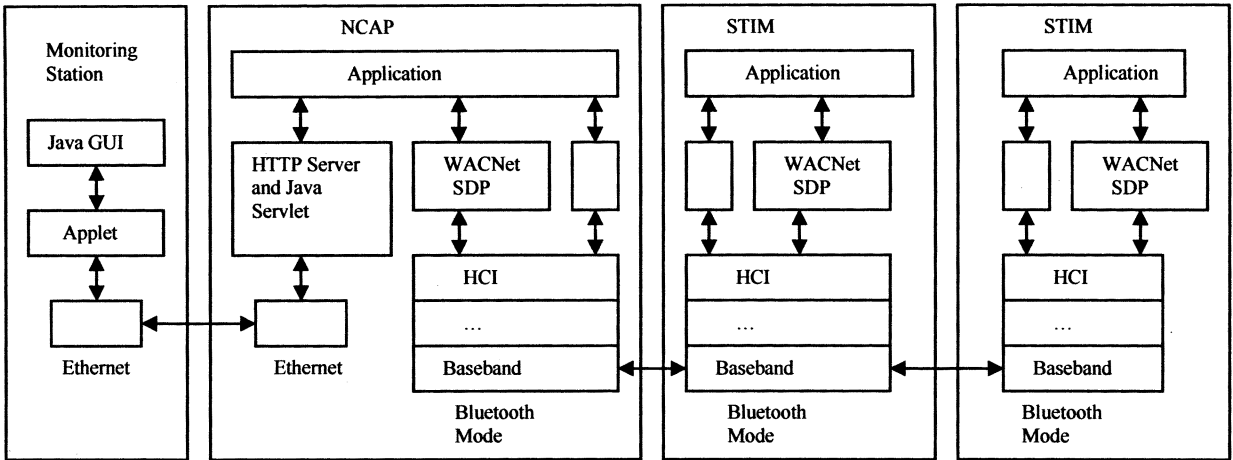Fig. 8 Request and response of Servlet and Applet

Fig. 9 Software stack implementations for WACNets

When the users connect to the TINI board via a web browser, they are presented with a Java applet providing them with a Graphical User Interface (GUI) to the system. The applet then uses standard HTTP requests to call the servlet in the TINI board and provides the servlet functions it requires to be executed.

C. Stack implementation of proposed system

The stack implementation for various components of WACNet is illustrated in Fig. 9 [10], which visually describes how appliances interrelate. Monitoring station can communicate with NCAP via Ethernet physical layer, and STIM can communication with other STIM nodes or NCAP nodes via Bluetooth Module.

V. SERVICE DISCOVERY

Service discovery refers to the ability of network devices, applications, and services to search out and find other complementary network devices, applications, and services that are needed to properly complete specified tasks [8]. Service discovery has been found essential for WACNet in implementing automatic discovery of networked devices, and remote control of one device from another.

The existing Service Discovery Protocols like SLP, Jini and UPnP are designed with traditional wired network in mind, which have quite different characteristics from WACNet. The Bluetooth Service Discovery Protocol is based on connecting to a specific node and querying about its available services. When the network becomes larger, the protocol of querying every single node in the network about the possibly unavailable services wastes both time and resources. A protocol to achieve service discovery should therefore be developed for WACNet.

The architecture of Service Discovery Protocol (SDP) in the proposed system is a hybrid of client-server and peer-to-peer protocols. In the clusters, masters are considered as server-like devices that reduce communication cost as search and service advertisement messages are addressed to particular devices instead of broadcast to the entire network. The Service Discovery is implemented through a number of service operations as described below.

A. Service Registration

When a new STIM node enters into the network, it sends

a *JoinClusterRequest* message with all Group IDs it has in the Channel_TEDSs to a nearby master, requesting permission to join the cluster. The master receiving this message will compare the received Group IDs with its own Group IDs. If there is no equal Group ID, the master disconnects the new STIM node. Following that, the STIM node will send *JoinClusterRequest* messages to other masters. Otherwise, the master will reply a *ServiceRegistrationRequest* to this STIM, which will become a slave node. This slave will send a *ServiceRegistrationReply* containing corresponding information. The whole process is illustrated in Fig. 10.

Every master node keeps a service record for each slave in the cluster. The service records will also be backed up in the bridge node, which is employed to connect with other clusters. The master will then send updates to the Backup devices whenever a change occurs in the service records. This process is illustrated in Fig. 11.
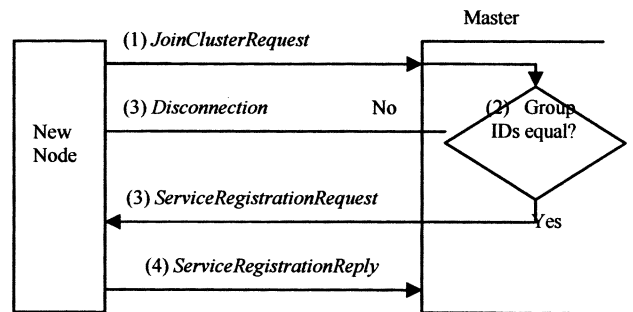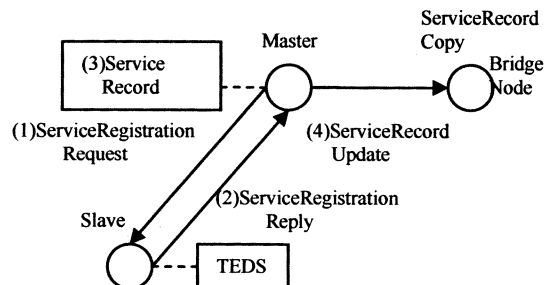

Fig. 10 The Service operations to join a cluster

Fig. 11 Service Registration

The numbers in the brackets shown in Figures 10 and 11 denote the order in which the packet is transferred.

To discover a node with particular service ability, the slave node will first send a *ServiceRequest* message to the corresponding master node, and the master node will check its service record table. If a match occurs, the master node will send a ServiceReply message back to the slave node. If the requested service is not available in the piconet, this *ServiceRequest* message will be forwarded to the bridge node in the same piconet to check whether the requested service is available in the neighboring piconet (within the scatternet) or not.

When a user looks for a node with particular service ability, the monitoring station will send a *ServiceQuest* message with Channel Type Key to the corresponding NCAP node, and the NCAP will check its service record table. If a match occurs, the NCAP node will send a *ServiceSearchRequest* message to the corresponding master node first searched. The master node will send a *ReadTEDSRequest* to the corresponding slave node. After receiving this message, the slave node replies with a *ReadTEDSReply* message to the master node. On receipt of this message, the master node sends a *ServiceSearchReply* message to NCAP nodes. This is eventually sent to the monitor station, via which, the user will get the required information.
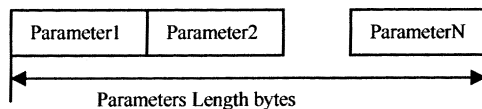
C. SDP_PDU Data Unite Format

Every SDP_PDU consists of a PDU header followed by PDU_specific parameters. The header contains three fields: a PDU_ID, a transaction ID and a Parameter Length, which is illustrated in Fig. 12.

PDU Header:

PDU_ID	Transaction ID	Parameter Length
1 byte	2 byte	2 byte

PDU_specific parameters:

Parameter1	Parameter2		ParameterN
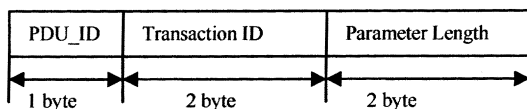
Parameters Length bytes

Transaction ID: Size: 2 Bytes

Value	Parameter Description
N	Transaction ID field uniquely identifies request PDUs and is used to match response PDUs to request PDUs.

Parameter Length: Size: 2 Bytes

Value	Parameter Description
N	The parameter Length field specifies the length (in byte) of all parameters contained in the PDU.

Fig. 12 SDP _PDU Data Unite Format

VI. CONCLUSION AND FUTURE WORK

A novel architecture for the new generation of distributed control system called wireless ad-hoc control networks (WACNets) is proposed. In this paper, the concept is introduced, and its architecture and design are described. Following that, service discovery protocol developed for the system is presented.

While WACNet provides a flexible and robust approach for control systems, it creates some challenges which should be addressed to improve the effectiveness of such systems. For example, the common problems associated with a wireless network such as limited bandwidth and energy constraints should be taken into account. The throughput of the network may prove insufficient to transmit all the necessary measurements and control signals. Frequent transmissions also consume the reserved energy of the nodes more quickly.

Ideally, the data transfer over the communication links should be accurate, timely and reliable. However, any communication network inevitably introduces random delay and packet losses. The problem is more pronounced in wireless networks due to the limited spectrum, time-varying channel gains and interference. This can be attributed to the many complexities involved in an undertaking that requires that the fields of communication, computing, and controls to come together seamlessly.

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