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Physical Layer of Wireless Ad-hoc Control Networks

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Abstract

A new concept called Wireless ad-hoc control networks (WACNets), designed for distributed and remote monitoring and control is explored in this work. It is suggested that ad-hoc control networks are the next stage in the development of distributed control and monitoring. WACNet explores a framework for organic, evolutionary and scalable method of integrating a large number of nodes with sensing and/or actuation, local intelligence and control, data processing and communication capabilities. A combination of IEEE 1451 compliant Smart Sensor and Bluetooth standard is employed to develop the first generation test-bed for the study of WACNets. The concept is introduced and the design of the nodes is presented. The progress up to date and the results obtained are reported.

Key word: Wireless ad hoc control network, Bluetooth, distributed control

1. Introduction

Real time control systems are set for another major change with the emergence of highly networked embedded computers and new paradigms such as Ambient Intelligence (AMI) which attempts to push the integration provided by ubiquitous computing one step further. Integration and networking are essential as the increasing number of embedded systems should collectively carry out complex tasks.

Control networks have been widely used in industry as a substitution of traditionally centralized or hierarchical control systems, where many dumb remote points (sensor and actuators) are connected to a central processor directly or through PLCs by point-to-point [1], because of their advantages of low-cost, low complexity and low failure. In these kinds of control networks, the processing functions of these modern complex systems are distributed over several physical nodes, each of which dedicates to a part of control process and to a group of sensors/ actuators. These nodes cooperate with each other, and communicate through a shared physical channel.

A new concept called Wireless ad-hoc control networks (WACNets), designed for distributed and remote monitoring and control is explored in this work. It is suggested that ad-hoc control networks are the next stage in the development 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 WACNetwork.

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-organising and cooperative capabilities for random deployment of the nodes. This implies that a node has ability to change its behaviour 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 variety of applications including environmental control of large buildings complexes, smart home control for security, identification and personalisation, 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 [3]. They can have direct applications in commercial, industrial, agriculture, health and defence sectors. There are also possible applications in personal and institutional security, radiology, and medicine.

The proposed system offers capabilities that do not currently exist in the control systems available from industry including:

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

In the course of the paper, the concept is initially described. The design of the nodes will be presented and the progress up to date will be provided.

2. System Overview

A wireless ad hoc control network (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 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 nodes are not mobile. But 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. A typical WACNet for building services is illustrated in Figure 1.

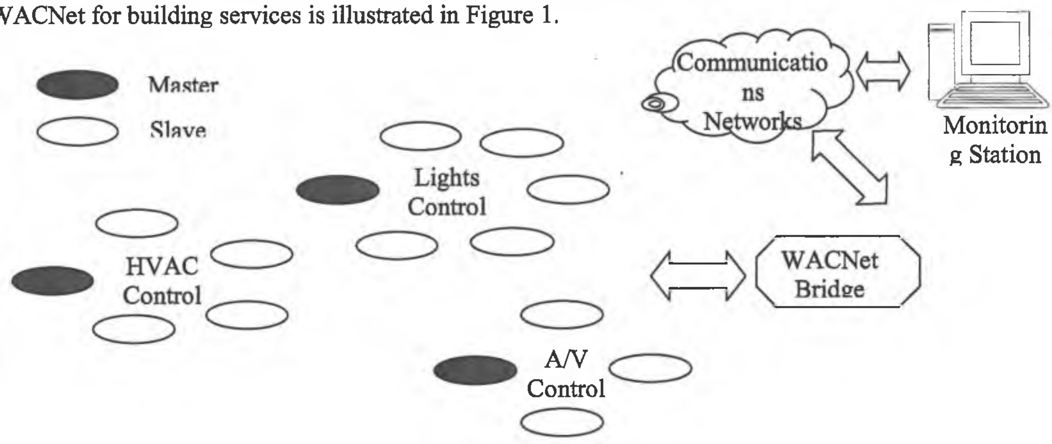

Figure 1 A typical WACNet for building services

In the proposed system, a combination of IEEE 1451 [2] compliant Smart Sensor and Bluetooth standard is employed to develop the first generation test-bed for the study of WACNets. In this structure, an intelligent or smart transducer (STIM) is formed by the integration of an analog or digital sensor or actuator element, a processing unit, and wireless communication unit (Bluetooth). This implements several advanced features such as plug-n-play while maintaining minimum hardware overhead at the sensor node.

The IEEE1451 family of standards (IEEE1451.1 and IEEE1451.2 and others) describes a framework for the construction and use of Smart Sensor units [3]. Smart Sensor units are like other sensor units, with one major difference. They have the ability to provide self-identification, self-testing and adaptive calibration [4]. One or more Smart Sensor units form a smart sensor network, whose purpose may be to collect data from distributed sources and transport it to a centralised location (host computer) for monitoring. Overall, IEEE1451 standard provides genuine distributed measurement and control [3].

Bluetooth has been employed because of the following reasons:
(a) It offers a low-cost, short-range wireless technology
(b) It is a suitable technology for various mobile devices
(c) It has mall power consumption
(d) It uses a frequency-hopping algorithm in order to avoid disturbance at a certain frequency, which offers higher robustness and scalability than fixed-frequency systems.

The structure of wireless implementation of IEEE1451 in this work is shown in Figure 2. As illustrated, STIM communicates with an NCAP module over a Bluetooth link. The TII protocol, which defines a form of serial communication between the STIM and NCAP, is implemented on top of the Bluetooth link layer. In this way, the TII link still looks like a normal serial link to higher-level software components (and can be used as such). The system under development implements several advanced features such as plug-n-play while maintaining minimum hardware overhead at the sensor nodes because of the deployment of IEEE 1451.

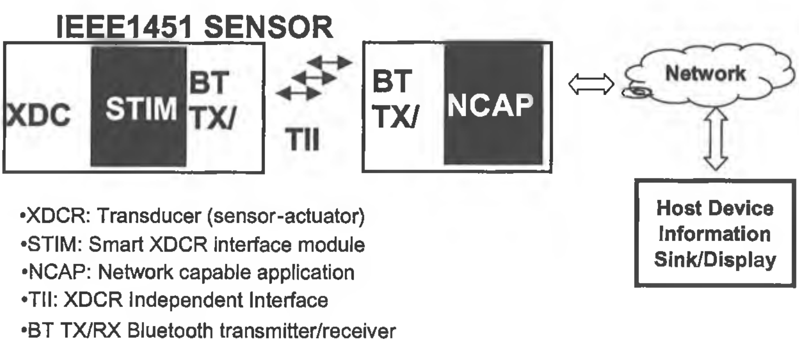

Figure 2 Wireless Model of WACNet

NCAP nodes are connected to the local monitor and /or control system that is implemented using a PC. An operator can monitor or control the whole system in real time through the local monitor system on demand [5]. Meanwhile, local monitor/control system is connected to a central monitor control system via the Internet. STIM and NCAP communicate each other via Bluetooth [6].

3. Realising WACNet Nodes

In the proposed system, STIM consists of the necessary elements to provide local sensing, actuation and control. The block diagram of the node structure is shown in Figure 3.

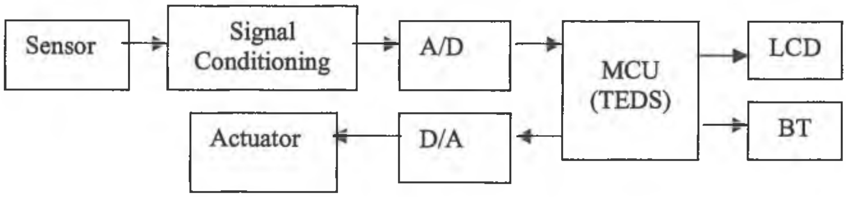

Figure 3 Architecture of STIM

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 sent to drive the actuator. With the deployment of Bluetooth wireless device, all data collected in the node can be transmitted wireless to a monitoring station.

In the first generation testbed of WACnet, the STIM part has been broken down into two parts: main board and communication board. A block diagram of the hardware device that is to be attached to the STIM is shown in Figure 4.

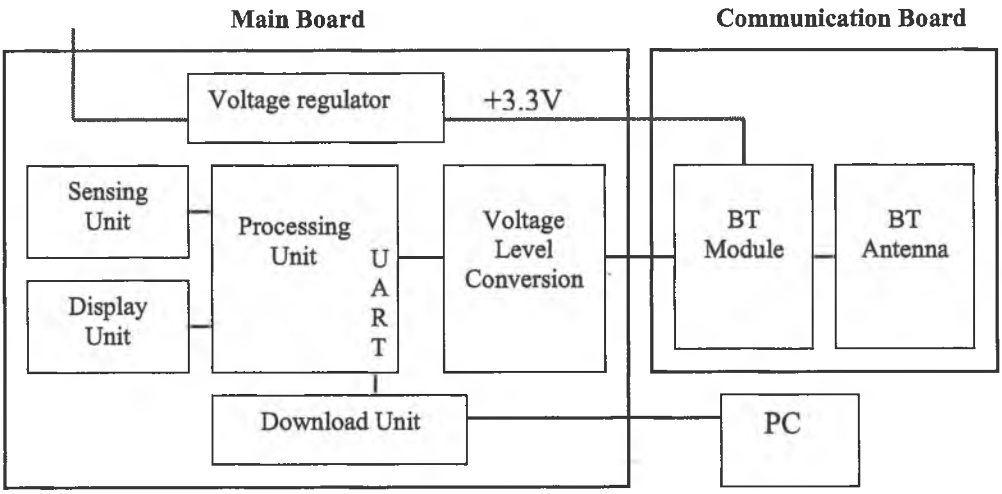

Figure 4 The Block Diagram of STIM

The NCAP module is equipped with both Bluetooth and Ethernet physical layer components, in order to provide a 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.

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 Figure 5 illustrates how the hardware devices interact.

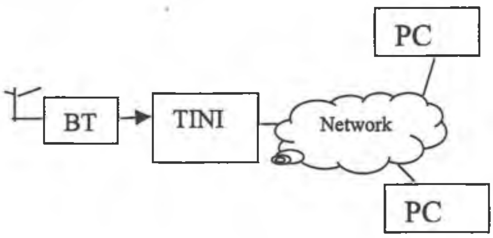

Figure 5 Block diagram

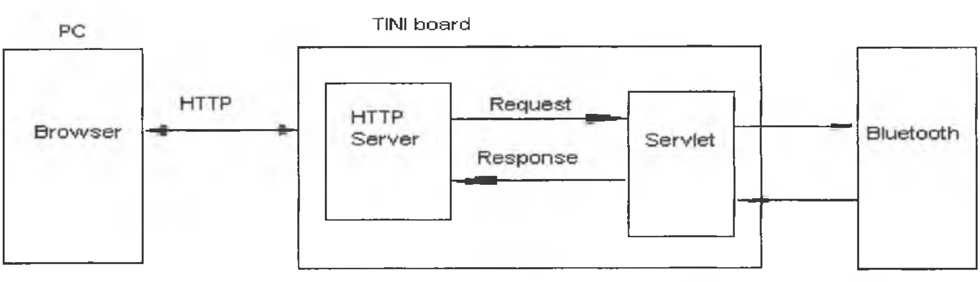

Figure 6 Request and Response of Servlets and Applets and Bluetooth

As users connect to the TINI board via a web browser, they are presented with a Java applet providing 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 servelt functions it requires to be executed. Figure 6 illustrates the interaction between a user and NCAP.

The node in this work is illustrated in Figure 7. 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 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 coloured metal cover of ROK provides an excellent RF shedding. It also has a 50 OM antenna interface for the best signal strength performance. Since PIC 16F877 does not have any USB interface, the ubiquitous serial communication interface, UART is used to communicate between the host and ROK 101 007.

Electronic interface between Microcontroller PIC 16F877 running on 5 V and Bluetooth module running on 3.3 V is achieved via two methods of discrete bipolar transistors and passive voltage divider for low-cost.

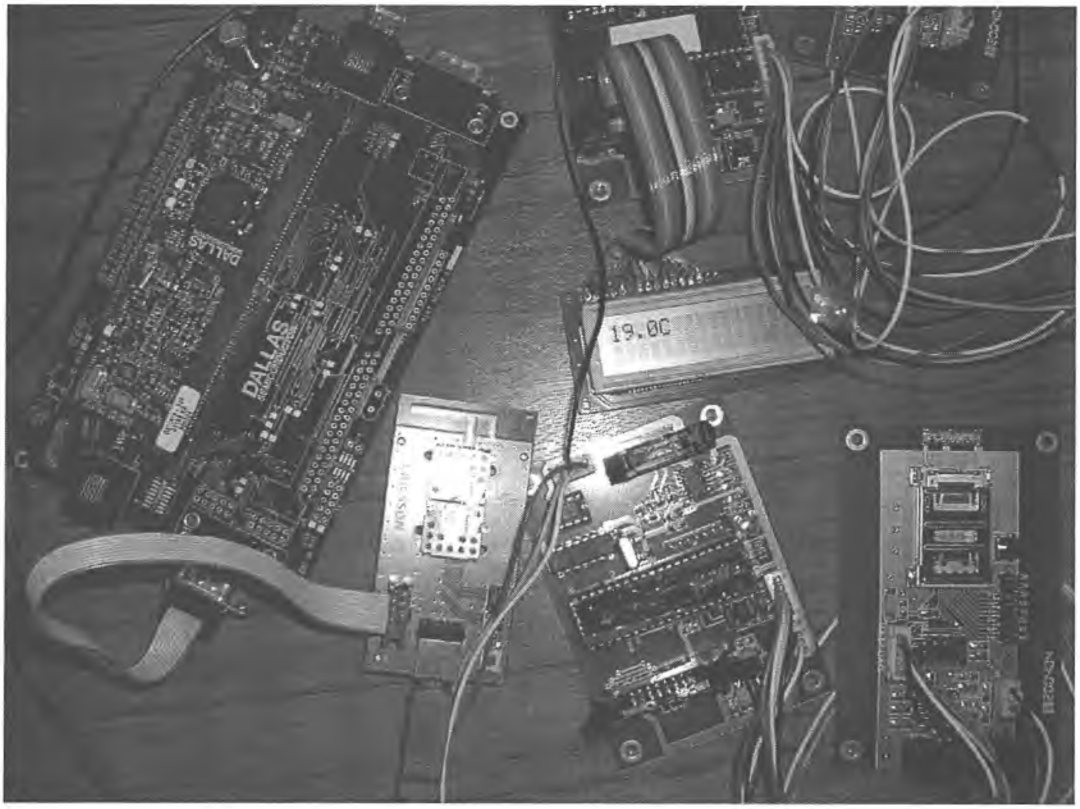

Figure 7 shows the development board used for the proposed system

In the node, the higher layer software, including application, SDP and L2CAP, is run on the PIC16F877 and lower layer one on Bluetooth module. Host Controller Interface (HCI) is used to provide the interface between the higher and lower layers. There are three different types of HCI packets exchanged between PIC16F877 and Bluetooth. HCI packets are carried on the HCI transport layer.

4. WACNet Operational Evolution

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

(a) Boot up: In this phase, the nodes are initialised 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 is satisfied that it has identified all of the other nodes that are within communication range, it is then ready to move on 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: The neighbouring nodes with common or complimentary functions form clusters of nodes and start to coordinate and synchronise their activities to achieve their common goal. Within a cluster, one node is the master of the cluster and the rest slaves. The master node coordinates and synchronises 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 the nodes. This information assists the nodes to match their services with the network requirements. This stage represents the first step in self-organisation 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 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 not performed by having the master of one cluster communicate directly with the master of another cluster. The transfer of information across the network is performed using a typical ad-hoc approach. Identification of the master node is made by identifying the role in the list of services offered by the node.

(e) Network Evolution: As the operation of the network evolves, new tasks might be expected from it which will be broadcast across the network. This will result in further self-organisation as described in stage (c). Further evolution can take place as the result of addition of new nodes due to:

- Failure of some of the nodes.
- The 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.

In the proposed system, STIM nodes exchange different information with monitoring stations via NCAP. Multihop is necessary in this system, because some of the STIM nodes are not in the communication range of NCAP. Namely, information from a STIM, which is not in the communication range of NCAP will be relayed by some other STIMs before it is finally transmitted to destination. Nodes communicate with each other via Bluetooth.

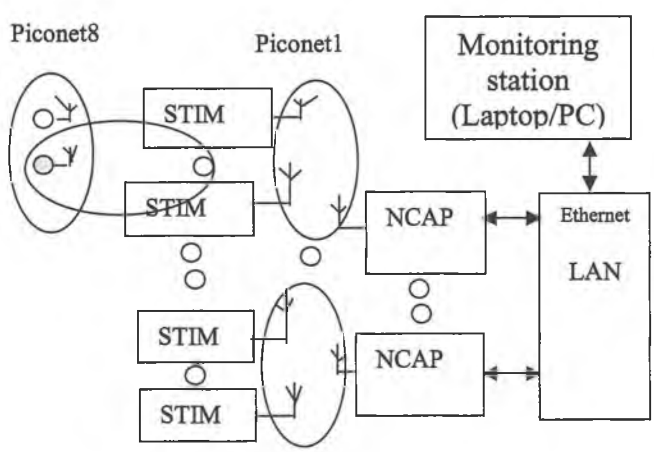

Figure 8 the Formed Whole Network System

5. Service Broadcast and 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 [7]. WACnet, ad hoc and peer-peer network, does not require a directory, instead relying on direct interactions between the devices themselves to determine each other's capabilities. In the dynamic ad hoc networking environment, the ability of service discovery is very important.

In the Bluetooth system, SDP can be deployed in the existing link. To establish a link, the higher layer protocol will send a request to the L2CA layer to connect. If there is no existing ACL connection, this causes L2CAP to send a request to a lower layer protocol to connect. In the lower level, the Bluetooth standard provides an inquiry procedure for device detection and a page procedure for connection establishment. The procedure called inquiry is unique to Bluetooth and is instrumental in making a connection possible. This procedure is necessary because Bluetooth units do not know anything about each other prior to connection establishment. Bluetooth SDP has the following characteristics: simplicity, compactness, versatility and service location by class and by attribute. In the WACnet, the Bluetooth SDP is modified to satisfy with the requirement of the first generation of the testbed.

The algorithms running in each node of WACnet ensure that the node is energy efficient and meets real-time requirements during scatterent formation. STIM's of the nodes form a hierarchical structure according to the power left in the node, the class of real-time requirements, and the distances to NCAP to the node. A parameter called Device Grade (DG) is assigned to each node reflecting the charactistics of the link of the node with the NCAP and the role its plays either as master, slave or bridge. WACNet is a real time system and hence the class of real-time requirements of nodes has the highest weight.

The nodes are heterogeneous in WACNet, as they satisfy different requirements. For example, in a building, light sensors need to update information back to monitor every several minutes. However, the temperature information does not change as fast. Hence, the real time constraint on light sensors is tighter than temperature sensors. For multiple clusters in the vicinity of an NCAP, the cluster with higher real-time requirements has higher priority to connect to NCAP than others. Other clusters might be forced to connect to NCAP via other clusters. In one cluster, the node with the highest power is selected a master or a bridge to ensure the stability of power efficiency of the scatternet.

These characteristics are encapsulated in equation (1) which defines how DG is calculated for a node.

$$DG = w_p * DeviceLeftPower + w_t * Class\,\mathrm{Re}\,altime - w_r * Dis\tan ceToNCAP \qquad (1)$$

$(0 < w_r < w_p < w_t < 1)$

w_r, w_p, w_t represent the weights for distance between the STIM and NCAP node, Power left in the device, and class of Real-time requirement respectively. In this equation, $w_r < w_p < w_t$, which shows that class of real-time requirement of task in the node is the most important parameter compared to the power left in the device, and distance to NCAP.

The information obtained during Service Discovery is stored by each node in a table which includes the logical addresses of the adjacent nodes, information related to routing and link connection, and services provided by them. The data structure is illustrated as following.

```
Class Bts
{
private byte[] BD_ADDR;
private byte[] CID;
private byte[] COD;
private byte[] ClockOffset;
private byte[] ConnectionHandle;
```

```
private byte PageScanRepetition;
private int DistanceToNCAP;
private byte PageScanPeriod;
private byte PageScanMode;
private Boolean isConnected;
private byte transducer_type;
private long DeviceLeftPower;
private int ClassRealTime;
}
```

6. Conclusions and Future Work

A novel architecture for the new generation of distributed control system called wireless ad-hoc control networks (WACNets) is proposed. The concept is introduced, and its architecture is described.

While WACNet provides a flexible and robust approach for control systems, it create some challenges which should be addressed to improve the effectiveness of such systems. For example, the ususal 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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