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Wireless Personal Area Networks architecture and protocols for multimedia applications

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Abstract: Wireless Personal Area Networks (WPANs) is an emerging technology for future short range indoor and outdoor multimedia and data centric applications. Two types of WPANs have been standardized by the IEEE 802.15 working group; namely: High data Rate WPANs (HR-WPANs) and Low data Rate WPANs (LR-WPANs). These standards define the network architecture, the physical layer and the medium access control sublayer for these systems. A tremendous number of performance studies through mathematical analysis and simulation have been published. Also, many products have appeared in the market which indicate a clear sign of a quick acceptance to the published standards. An organized review of the network architecture, the physical layer specifications, the Medium Access Control (MAC) protocols and the general network operation concepts of the WPAN systems deserves time and effort to be presented in a collective manner. In this paper we describe the concept of WPANs and its applications. Then, the communication architecture and the allocated frequency spectrum for WPAN operation are explained. The developed MAC sublayer protocols in the literature are explored.

Keywords: Wireless personal area networks, Wireless sensor networks, Multimedia applications, MAC protocols performance analysis, WPAN architecture

I. INTRODUCTION

As we gradually become surrounded by an increasing number of electronic devices, there is a growing demand for networking them together in a manageable and preferably wireless fashion. Therefore, Wireless Personal Area Networks (WPANs), which operate around a Personal Operating Space (POS), are expected to play an essential part in the 4G communication systems by enabling short-range wireless ad hoc connectivity[1-4].WPANs have some similarities with fixed Wireless Sensor Networks (WSNs) [5] with some important differences. For example, a WPAN is characterized by a small number of nodes and the specific group mobility pattern at pedestrian speeds. However WSN is composed of a large number of sensor nodes with a limited or static mobility.

Currently, two WPAN standards have been developed for advanced short-range wireless communications: IEEE 802.15.3 for High-Rate WPAN (HR-WPAN) and IEEE 802.15.4 for Low-Rate WPAN (LR-WPAN) [6,7]. The HR-WPAN defines the protocols and their primitives for supporting high rate multimedia and data communications over a short-range transmission channel [6]. On the other hand, LR-WPAN standard defines the protocols and their primitives for supporting low data rate communication also over a short-range transmission channels [7] . A WPAN network is featured with low-cost and very low power consumption nodes, ease of installation, reliable data transfer, and simple protocol structure [2]. In addition to the contention- based channel access mechanism, both of the standards adopt the Time Division Multiple Access (TDMA) for assigning one or more exclusive transmission slots to a single node in order to provide Quality of Service (QoS) for the supported applications.

A WPAN consists of several nodes communicate over a wireless channel. One of these nodes is required to assume the role of the network coordinator.2 The network coordinator starts the creation of a WPAN and allocates collision free time slots when requested by network nodes. Also, it controls the association and disassociation process of a node to the network. The WPANs standards are only defined for the physical and medium access control layers and are defined to operate over the Industrial, Scientific and Medical (ISM) frequency bands.

Following the standardization of the WPANs standards and their acceptance by the industry, the concept of WPANs communication systems has become the focus of extensive research to provide an excellent introduction to the protocol stack, design requirements and evolution to the drafts of the IEEE 802.15.3 and IEEE 802.15.4 standards [8,9] . Recently, the Medium Access Control (MAC) sublayer has been extensively studied to evaluate the performance of the WPANs standard MAC protocols through mathematical analysis and simulation as well as proposing and evaluating a new approaches to enhance and enrich these standards [1,4,10-12]

In this paper we conduct a comprehensive review for the proposed WPAN network architecture and its MAC protocols. Also, for providing a collective document for the state-of-the-art in wireless personal area networks, a comprehensive literature review of the performance evaluation and protocol enhancement for the proposed WPANs' MAC protocols is given.

This paper is organized as following, in Section 2 we give a brief explanation for the distinguishing points between the proposed WPANs and the well established Wireless Local Area Networks (WLANs). Also, we touch upon the targeted markets and applications for both HR-

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WPAN and LR-WPAN. Then the HR-WPAN network topology, the network nodes internal architecture and the HR-WPANs standard MAC protocol are presented in Section 3. In Section 4 we explain the LR-WPAN standard in which the LR-WPAN different network topologies, internal node architecture, and the standardized LR-WPAN MAC protocol are detailed. Then, a number of selected MAC protocol studies from the literature are presented in Section 5. The current possible research directions in the WPAN area given in Section 6. In Section 7 we give a conclusion for the main points presented in the paper.
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II. WPANs vs. WLANs

To understand the objective of developing WPANs, it is appropriate to classify them and define their applications which are designed for. WPANs may appear to be in competition with Wireless Local Area Networks (WLANs); IEEE 802.11 standard. However, many significant differences differentiate these network types. Fig. 1 illustrates the coverage ranges of these wireless standards and their achievable data rates.

WPANs are defined around the Personal Operating Space (POS) which typically extends up to 10m in all directions and envelops a person or an object whether stationary or in motion. WPANs are also defined for low cost, low power consumption, and very small size devices. The size of a WPAN node is the size of a compact flash card suitable for integrating it within handheld devices such as cellular phones and Personal Data Assistance (PDA). On the other hand, WLANs are classified as a long range systems with higher complexity to handle seamless roaming and message forwarding. A WLAN consists of a central node know as Access Point (AP) which manages the communication channel access to a number of end nodes. A typical WLAN node is designed as a PC card suitable for a desktop or laptop.

The most obvious characteristic of LR-WPAN is its data throughput, which ranges from 20 kb/s to 250 kb/s. Many applications require only limited bandwidth since they are only generating small amounts of data. These applications, such as monitoring and controlling industrial equipment, require long battery life so that the existing maintenance schedules of the monitored equipment are not compromised . Other applications, such as environmental monitoring over large areas, may require a large number of devices in which battery replacement of such devices is impractical. Another promising application for LR-WPANs is in the field of medical application where patient's health conditions can be monitored remotely via an on-or in-body sensor nodes . In such application, health information from a human body can be sensed using a special medical sensors and communicated via LR-WPAN, which is overlied over other communication technologies such as WLANs, to a remote health site where it can be diagnosed by health authorities.

On the other hand, HR-WPAN characterized by its high data rate transmission that ranges from 11 Mb/s to55 Mb/s. It is well suited for many applications which require large bandwidth to sustain their large traffic. These applications may include the distribution of real-time video generated by digital cameras and camcorders that

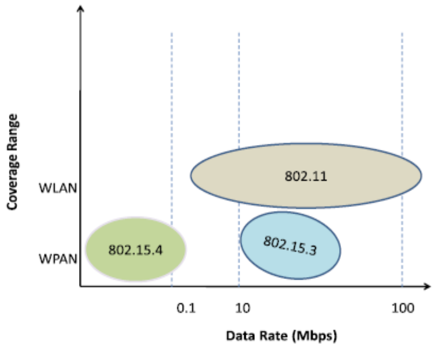

Fig.1. WPAN and WLAN operating space

can store multi megabytes image files and video streams in digital format. Also, a high-quality audio and video can be carried by HR-WPANs. One such popular application is wireless playback feature of a digital camcorder on a TV screen. Another application for HR-WPAN can be found in the area of interactive gaming which is built around 3D graphics and high-quality audio. HR-WPAN can be used to establish the wireless links between multiplayer game consoles and high-definition displays.

III.HIGH RATE WIRELESS PERSONAL AREA NETWORKS

The High-Rate Wireless Personal Area Networks (HR-WPANs) standardized in [6] are presented in this section. First, the network topology and the network nodes classifications and functionalities are explained in Section 3.1. Then, we explain the layered architecture of the network nodes in Section 3.2.

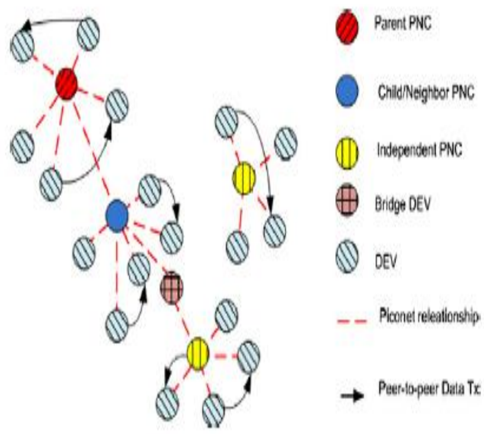

Fig.2 HR-WPAN network topology

A. HR-WPAN network topology

An HR-WPAN topology consists of several nodes that implement a full or a subset of the standard. The HR-WPAN is called piconet and the network nodes are known as Devices (DEVs) [8]. The formation of a piconet requires one node to assume the role of a Piconet Coordinator (PNC) which provides synchronization for the

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piconet nodes to the periodically transmitted PNC beacon frames, support quality of service, and manage nodal power control and channel access control mechanisms. The HR-WPAN topology is created in an ad hoc manner which requires no preplanning and nodes can join and leave the network unconditionally.

There are three types of piconet topologies which are defined in the standard:

- Independent piconet,
- Parent piconet,
- Dependent piconet

The neywork topologies of these piconets are shown in Fig. 2 and their characteristics, the objective of their creation and their nodes functionalities are detailed in the following.

(1) Independent piconet: An independent piconet is a stand alone HR-WPAN which consists of a single network coordinator and one or more network nodes. The operation of this piconet type does not depend on other HR-WPANs. . The network coordinator manages the network operation through the periodically transmitted beacon frames in which other network nodes use to synchronize with to be able to communicate with the network coordinator as well as performing peer-to-peer communication. The

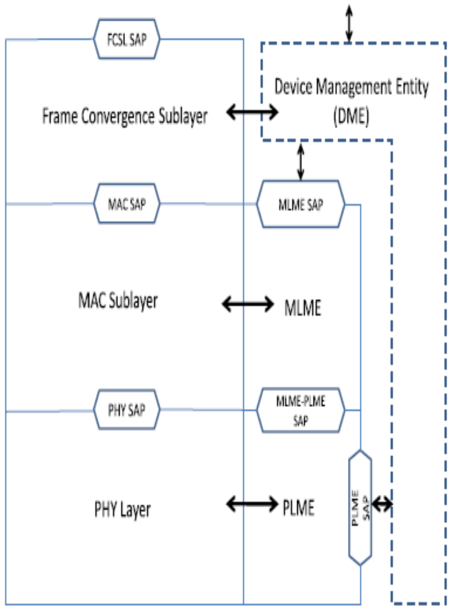

Fig. 3. Generic HR-WPAN layered node Architecture

independent piconet topology is shown in Fig. 2 which can be inferred by its independent PNC. The independent piconet can communicate with another adjacent independent piconet through a Bridge node which is also shown in Fig. 2

(2) Parent piconet: A parent piconet is a HR-WPAN that controls the functionality of one or more other piconets. In addition to managing communication of its network nodes, the network coordinator of the parent piconet controls the operation of one or more dependent network coordinators.

(3) Dependent piconet: Dependent piconets are classified according to the purpose of their creation into ‘‘Child’’ piconet and ‘‘Neighbor’’ piconet. A child piconet is created by a node from a parent piconet to extend network coverage and/or to provide computational and memory resources to the parent piconet. The resources allocation such as Channel Time Allocation (CTA) for network nodes in such piconet is controlled by the parent network coordinator node.

The other dependent piconet, the neighbor piconet, is created by the neighbor piconet coordinator which is not a member of the parent piconet. The purpose of associating a neighbor piconet with a parent piconet is the lack of a vacant frequency channel for the creation of an independent piconet. Therefore, a neighbor piconet can be created and the radio channel resources of such network will be allocated by the parent network coordinator.

B. HR-WPAN node architecture

The reference model of the HR-WPANs node architecture is shown in Fig. 3. This model defines the architecture into two parts; namely: node structural blocks part and node management part. The node structural blocks part is mainly composed of three layers; Frame Convergence Sublayer (FCSL), MAC sublayer, and Physical (PHY) layer. The HR-WPANs standard is defined only for the MAC and PHY layers where each layer implements a subset of the standard and offers services to its upper layers and gets services from its lower layers. The FCSL interfaces the MAC sublayer to the upper layers such as the networking layer, application layer, etc.

The management part of a HR-WPAN node consists of the Device Management Entity (DME). The DME facilitates the functionalities of the MAC and PHY layers and other upper layers. It is a layer-independent entity and can be resided in a separate management plane. The detailed functionality of the DME is not specified by the standard. However, gathering layer-dependent status from the management entities of different layers and setting the values of layer-specific parameters are examples of DME duties.

The DME is interfaced to the MAC sublayer and the PHY layer through designated Service Access Points (SAPs) of the MAC subLayer Management Entity (MLME) and the PHY Layer Management Entity (PLME) respectively. The DME should be present in each node for correct node operation.

The services provided by the physical and medium access control layers are briefly explained below.

(1) Physical layer services: The physical layer of the HR-WPANs defines the procedures of transmitting and receiving data between two or more network devices through a wireless channel. The physical layer contains two functional entities; namely: PHY function and PLME function (see Fig. 3). The PHY layer services are provided to the MAC sublayer through the PHY’s SAP. The main tasks of the PHY layer are the activation and deactivation of the radio transceiver, Link Quality Indication (LQI), Clear Channel Assessment (CCA), and transmitting as

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well as receiving data packets over the physical medium. The LQI is a measurement task performed by the physical layer. The LQI is reported for the Trellis Coded Modulation (TCM) coded QAM modes using
the estimation of the Signal to Noise Ratio (SNR). LQI is a characterization of the strength and the quality of a received signal. The use of LQI result is up to the network or application layers. The CCA is used to evaluate the wireless channel activities before a node can start data transmission. This mechanism is used to minimize packet collisions. Therefore, a node with queued data is required to first sense the transmission medium for a random period of time through the CCA procedure. If the PHY layer informs the MAC sublayer the medium is idle, the node starts data transmission. This process of waiting before transmission is known as backoff process. The backoff procedure is not applied to the transmission of the periodically transmitted beacon frames by the PNC node.

(2) MAC sublayer services: The MAC sublayer of the HRWPANs is designed to achieve a set of goals. These goals are: Supporting fast connection time, Ad hoc networks topology, QoS support, dynamic node membership, efficient data transfer, and secure data
communication. The MAC sublayer achieves these goals through two services: the MAC data service and the MAC management service. For data communication, the MAC sublayer communicates with the FCSL through the MAC SAP and being serviced by the PHY layer through the PHY SAP. The management entity of the MAC suplayer; MAC subLayer Management Entity (MLME) communicates with the DME through the MLME Service Access Point (SAP) (MLME-SAP). The features of the MAC sublayer are beacon management, channel access control through the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme, collision-free channel time allocation for management information and data communication, frame validation, acknowledged frame delivery and node association and disassociation.

IV. LOW-RATE WIRELESS PERSONAL AREA NETWORKS

The Low-Rate Wireless Personal Area Network (LR-WPAN) architecture as presented in the IEEE standard [7] is briefly described in this section. First, we explain the network topology and the node classifications and functionalities for LR-WPANs in Section 4.1. Then, the LR-WPANs nodal architecture is explained in Section 4.2. The allocated spectrum for the LR-WPAN

C. *LR-WPAN network topology*

The IEEE 802.15.4 standard has defined two different network topologies to suite different application requirements; namely star and peer-to-peer topologies . The star network topology is shown Fig. 4a and the peer-to-peer network topology is

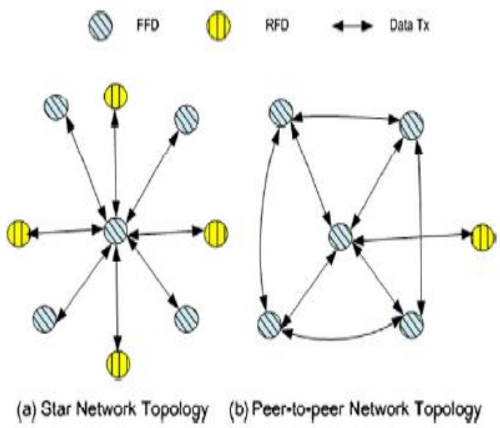

Fig. 4. LR-WPAN network topology.

shown in Fig. 4b. These network topologies consist of different devices which are classified by the standard into Full Function Device (FFD) and Reduced Function Device (RFD). The FFD implements all features of the IEEE 802.15.4 standard and can serve as a regular device or as a network controller known as Personal Area Network (PAN) coordinator. Also, the FFD can serve as a relaying node in a LR-WPAN mesh network topology or as an end node performing only specific duty. On the other hand, RFD implements the minimum required functionalities by the standard and can only function as an end node such as temperature sensor or a light switch which communicates its sensed information only to the PAN coordinator of its network. The characteristics and the targeted applications of each network topology are given below.

(1) Star network topology: The star network topology is composed of a PAN coordinator and a number of FFD and/or RFD nodes. When beacon-enabled MAC frame structure is used, network devices synchronize their communication with the PAN coordinator through the periodical transmission of the coordinator's beacon frames and they use slotted (CSMA/CA) for accessing the transmission channels. Also, the PAN coordinator allocates, upon nodal request, collision- free time slots for supporting mission-critical services. However, when nonbeacon-enabled frame structure is used, there is no beacon frames transmission by the coordinator and the unslotted CSMA/CA is used instead for accessing the transmission channel.
The communication in the star network topology is established between network devices and the PAN coordinator. A network node with an associated application can be the communication initiation or termination point. Also, the PAN coordinator may have a specific application but also can be initiation and/or termination communication point as well as routing communication in the network. A variety of applications can benefit from the star network topology. Some of these applications are health care applications, personal computer peripherals, home automation and games.

(2) Peer-to-peer network topology: A peer-to-peer
LR-WPAN topology is an ad hoc, self-organizing and self-healing network topology. It is also formed around a PAN

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coordinator but differs from the star network topology in which any device may have a peer-to-peer communication with any other device in the network through a single hop or multiple hops. Complex network topologies can be created which facilitate the formation of mesh networking topology. Only nonbeacon-enabled MAC frames with unslotted CSMA/CA channel access mechanism are used in the Peer to peer network topology. The targeted applications for peer-to-peer network topology are industrial control, monitoring, wireless sensor networks, inventory tracing, etc.

D. LR-WPAN node architecture

Fig 5 shows a generic LR-WPAN node architecture. The node architecture is defined into a number of structural blocks called layers. Each layer implements a subset of the LR-WPAN standard and offers services to its upper layers and gets services from its lower layers. The layered architecture of each network node comprises Physical (PHY) layer and Medium Access Control (MAC) sublayer. On top of these layers is the Service Specific Convergence Sublayer (SSCS) which interfaces the MAC sublayer to the logical link control sublayer and other upper layers such as the networking layer, application layer, etc. The LR-WPANs standards are defined only for the physical layer and medium access control sublayer while other layers' specifications are undefined in the standards. The services provided by the physical and medium access control layers are briefly explained below.

(1) Physical layer services: The physical layer provides two services: the PHY data service and PHY management service interfacing to the Physical Layer Management Entity (PLME). The PHY data service enables the transmission and reception of PHY Protocol Data Units (PPDU) across the physical radio channel. The main tasks of the PHY layer are the activation and deactivation of the radio transceiver, channel Energy Detection (ED), Link Quality Indication (LQI), Clear Channel Assessment (CCA), and transmitting as well as receiving data packets over the physical medium. The ED measurement estimates the received signal power

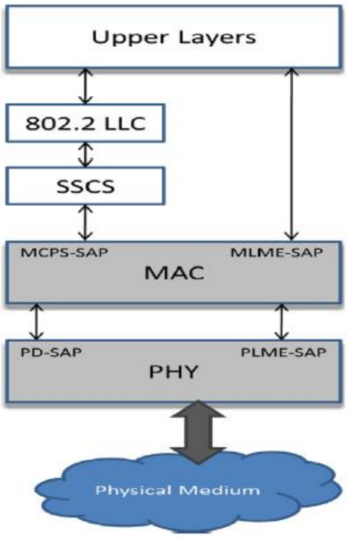

Fig. 5. Generic WPAN layered node architecture

within the bandwidth of the LR-WPAN channel during both channel scanning phase and packet reception phase on an active physical channel. The measured value is used by channel selection algorithm at the networking layer.

The LQI is another measurement task performed by the physical layer for each received packet. .It is a characterization of the strength and the quality of received packet. The measurement may be implemented using the ED mechanism or the signal-to noise estimation procedure or a combination of these methods. The use of LQI result is up to the network or application layers.

The CCA task is performed by the PHY layer to evaluate the current transmission channel status; busy or idle. Three modes are used to perform (CCA) task. These modes are:

- *CCA Mode1* – Energy above threshold: A busy medium signal is reported when the channel's detected energy level is above the ED threshold
- *CCA Mode 2* – Carrier sense only: A busy medium signal is reported upon the detection of a signal with the same modulation and spreading characteristics of the PHY that is currently in use by the device even if the detected signal is below the ED threshold.
- *CCA Mode 3* – Carrier sense with energy above threshold: A busy medium signal is reported only when carrier sense with energy level above the ED threshold.

(2) MAC sublayer services: The MAC sublayer provides two services: the MAC data service and the MAC management service interfacing to the MAC subLayer Management Entity (MLME) Service Access Point (SAP) (MLME-SAP). The MAC data service enables the transmission and reception of MAC Protocol Data Units (MPDU) across the PHY data service. The features of MAC sublayer are beacon management, channel access control through the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme, collision-free time slots management, framevalidation acknowledged frame delivery and node. association and disassociation.

V. WPAN open research problems

The WPAN is still in its early development stage and much work still needs to be done; power management, efficient resource allocation algorithms, efficient nodal association mechanisms, efficient channel scanning algorithms, enhanced QoS-based MAC protocols, just to name few. For example, nodal association mechanism needs to be investigated in depth to minimize nodal association time and minimize the consumed power during this process through an effective scheduling mechanism. Other research direction is the overlaying of WPANs over another communication technologies such as WLAN or cellular systems. Unless it is overlaid over other long-range communication systems, some of the WPAN applications will not be supported such as medical application. The reason is that, the WPAN collected information needs to be communicated to a remote site to be analyzed, which can not be done by the short-range WPAN systems itself. Therefore, an overlaying testbed could be beneficial to evaluate the performance of the

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WPAN overlaid over the performance of the WPANs overlaid over other communication technologies.

IV. CONCLUSION

A comprehensive study of the architecture and protocols of Wireless Personal Area Networks (WPANs) has been conducted in this paper. The objectives of introducing these new communication paradigms have been given first along with a brief comparison with WLAN systems. The proposed network architecture for low rate and high rate WPANs and the differences among these network topologies have been described. Also, the proposed MAC protocols for these WPANs have been explained in a detailed manner. Then a selected number of papers evaluating the performance of the proposed WPANs MAC protocols has been explored. Some of the still open research avenues in the WPAN networks, which need to be investigated to enhance WPAN performance have been also summarized. The flexibility, low-cost and low power consumption characteristics of the WPANs will help create many new and exciting applications. In the future, this wide range of applications will make WPANs an integral part of our lives.

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