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Study of multiplexing and switching strategies in Bluetooth v3.0 hybrid radio system and for VHDR WiMedia/60 GHz multiband radio system

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Abstract

This is deliverable D5.2.1 of EUWB WP5, a study of hybrid radio strategies. It discusses Bluetooth / WiMedia and WiMedia / 60GHz hybrid systems, and describes the rational behind such systems. It contains an explanation of a strategy for switching between the different RF technologies in hybrid radio systems, to support the multiplexing requirements of possible applications. It identifies service discovery and power optimisations. It investigates potential prototyping platforms.

Keywords

Multi-mode, Multi-band, Hybrid Radio, Bluetooth HDR, WiMedia, 60 GHz, Switching, Multiplexing

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Terms & Abbreviations

BoD	Bandwith on Demand - a layer provisioning more resource only when throughput on the data stream requires it. This term is used at a device level to refer to the set-up and tear-down of a physical channel.
Bonding	A means by which data from a single stream can be sent across multiple channels or mediums in a manner transparent to the higher layers, thus improving reliability and throughput.
Channel	A discrete data flow path over the physical medium.
Codec	A conflation of "code" and "decode". This is a transformation which converts one form of encoding into another e.g. mp3 to wav, or DivX into uncompressed (for display)
DRP[6]	Distributed Reservation Protocol. A MAC access method which reserves a particular time slot within the time multiplexed wireless medium
HDR	High Data Rate - no absolute meaning just used in contrast to LDR
Leaky bucket algorithm	Buffering of sporadic data (sometimes from more than one source) in order that data on a stream can be transmitted in a smooth manner, so improving the predictability of the resources required on the medium. This comes at the expense of latency.
LDR	Low Data Rate - no absolute meaning just used in contrast to HDR
Link	A logical connection between two peer layers. Although messages concerning a link must be exchanged on the data plane, in the BoD situation there is no necessity for there to be an active stream associated with it.
MAC[6]	Medium Access Controller - a layer of the stack which negotiates the use of the available wireless spectrum such that multiple devices can share it.
OOB	Out Of Band - the transmission of a packet over channel with which it is not normally associated.
QoS	Quality of Service - the provision of different levels of priority to different applications, users, or data flows, or to guarantee a certain level of performance to a data flow in terms of rate and / or latency.
Packet Scheduler	A software entity which is configured to provide suitable QoS streams and schedules packets on them.
PCA[6]	Prioritised Connection Access. A MAC access method by which data is sent "best effort" in unreserved slots and the empty portion of slots on the medium.
PPP[15]	Point-to-point protocol - a protocol stack defined by the IETF to provide data-link level connectivity. It provides multi-channel bonding, QoS, and BoD.
Rate Adaption	In normal use, many applications vary their throughput requirements. Rate adaption is a method used by the MAC to negotiate a change in its allocated slots.
Stream	A logically discrete flow of data over a link. Depending on the layer, the data on a stream may be grouped by originating application, QoS requirements or intended physical medium.

Tunnelling	The wrapping of a message of one protocol in another so that is may be transmitted across an alternative medium. At the other end it is unwrapped to re-cover the original message.
WiMedia[6]	A 350+ member global non-profit organisation, that defines, certifies and supports enabling wireless technology for multimedia applications based on MB-OFDM UWB radio technology.

1 Executive summary

EUWB[2] WP5 will provide enhanced UWB platforms in terms of throughput and flexibility by introducing multimode and multi-band architectures. Multimode multi-band operation, in this context, is not intended as a mere bridging application from one physical layer to another. Instead the differing protocols and physical layers are used in a coordinated manner to provide a superior point-to-point connection. This connection is then used to provide the differing QoS requirements for multiple applications. Speed, efficiency and superior service discovery are the hallmarks of such a hybrid radio system.

By building upon the deliverables from PULSERS Phase II WP2a [8][9] and referring to the latest state-of-the-art specifications, this deliverable provides an investigation into the multiplexing and switching techniques required to support the concept of a hybrid radio system for two differing approaches using UWB radio technology;

1. Bluetooth / WiMedia Hybrid Radio System (Bluetooth HDR)
2. WiMedia / 60GHz Hybrid Radio System

Having identified existing protocols and standards for the support of heterogeneous networks, this study suggests the IETF architecture for point-to-point communications provides a suitable host framework for the basis of a hybrid radio system. The IETF architecture has been shown to provide support for connections over multiple logical links which may in turn be supported by one or more physical channels, as supported by one or more radio sub-systems in a hybrid radio system.

This study has concludes that;

1. The IETF architecture and the existing Bluetooth SIG specifications provide a clear framework for development of a Bluetooth HDR hybrid radio.
2. The (V)HDR platform from WP7, in combination with a COTS Bluetooth dongle, would provide a suitable development platform for a Bluetooth HDR implementation of the concepts proposed in section 5.1 of this study.
3. There is insufficient correlation of the code base of a WiMedia MAC implementation and a 60GHz MAC implementation to permit a simple migration from one to another.
4. It may be possible to use a bottom up approach that implemented a suitable MAC for 60 GHz by starting with the re-targeting of the base layers of a WiMedia MAC to bootstrap a 60 GHz stack,

It is therefore the recommendation of this study that the development, implementation and verification of the software sub-components required to support a Bluetooth HDR solution could proceed in EUWB task 5.2.2, with the integration of such a system in task 5.2.3 using the (V)HDR deliverable from WP7.

Alternatively, it would be possible to consider adaptation of the lower parts of an existing WiMedia MAC to support the features and functionality required by a 60GHz MAC in task 5.2.2, with the integration of this component with a suitable 60 GHz PHY in task 5.2.3. This could provide a development platform with limited functionality suitable for further commercialization.

This study concludes that it is unlikely there is sufficient effort and budget to develop a full (V)HDR WiMedia/60 GHz multi-band radio system development to include PAL/MAC, BB, RF within the scope of EUWB tasks 5.2.2 and 5.2.3 at this time.

2 Introduction

EUWB WP5 will provide enhanced UWB platforms in terms of throughput and flexibility. This will be achieved by introducing multimode and multi-band architectures. The multimode multi-band operation will provide a combination of multiple or similar physical layers in a hybrid radio system. This will provide different capabilities to support QoS requirements for multiple applications. It is in contrast to a bridging application from one physical layer to another which merely translates from one technology to another.

This deliverable provides an investigation into the multiplexing and switching techniques required to support the concept of a hybrid radio system for two differing approaches using UWB radio technology;

1. Bluetooth / WiMedia Hybrid Radio System (Bluetooth HDR)
2. WiMedia / 60GHz Hybrid Radio System

Although in each case the wireless technologies are quite different, it is thought that the fundamental approach to multiplexing and switching would be broadly similar. Therefore, this document discusses the options for multiplexing the control and data paths in a Bluetooth HDR system and a WiMedia/60GHz system.

2.1 Overview

There are many wireless standards in existence, each of which addresses different requirements in terms of flexibility, throughput and operating environment. A hybrid heterogeneous device is one which contains more than one radio subsystem and implements more than one radio standard. The aim of such a device is to provide a service which exhibits the advantages of both. Preferably in a manner which is straight forward to the software at higher layers.

The nature of those advantages, and the potential form that such a hybrid device might take, are the background element of this study. The capability of an application to multiplex data with different transmission requirements is addressed. The means by which an application would be able to appropriately switch between the devices' configured technologies is also examined.

A view is taken on the extant technology and intellectual property, with the intention to progress the development of such a hybrid device.

2.2 The Case for Heterogeneous Wireless Links

The ECMA-368 UWB standard, as defined by reference [6], is based on the UWB MAC and PHY specifications developed by the WiMedia group. WiMedia UWB radio systems offer high data rate (HDR) and spectrum utilisation advantages over traditional narrowband radio systems. Typically, they present lower energy per bit and higher data rates (of up to 480Mbps for WiMedia specification version 1.2). WiMedia based solutions are, however, resource hungry in the case where applications require limited amounts of intermittent data transfer.

Whilst 60GHz radio technology, such as that described by reference [5], the ECMA-387 60 GHz standard, offers extremely high data rates (of up to 6 Gbps) but it is prone to environmental interference due to its short wavelength. In particular, it does not pass through or around obstacles, and has a short range as it is absorbed by water vapour.

The Bluetooth radio standard operates in the globally unlicensed 2.4 GHz ISM band and offers mature enquiry, service discovery and association methods, coupled with low power features. These represent significant advantages over the WiMedia and 60GHz specifications which only address service discovery and application profiles in a limited way. Bluetooth also has wide-scale adoption in mobile devices e.g. laptops and mobile phones. This is particularly apposite in regions where support for other short range radio technology is limited by restrictions imposed by local wireless regulations.

As a result, hybrid devices can support a lower power, lower data rate radio channel to maintain a link such as that offered by Bluetooth radios, whilst bringing up the fast links (on radios offering significantly higher data rates) only when the application requires that level of throughput. The multiplexing and switching techniques used to support such a capability in a hybrid radio system forms the body of the study reported by this document.

In order to match the profiles of the applications to those of the wireless technologies, the strengths and weaknesses of the Bluetooth, WiMedia and 60 GHz radio technologies are discussed individually and the attributes are correlated.

Potential hybrid radio combinations are identified. The specific issues arising from the combination of Bluetooth / WiMedia and WiMedia / 60 GHz hybrid radios are discussed in more depth, with a particular view to fulfilling potential use-cases.

Strategies for the implementation of their multiplexing are examined, and suitable switching strategies are discussed in more depth. Gaps due to the partial implementation or undeveloped nature of the technologies are identified. This leads to the identification of the implementation and verification options for both "Bluetooth / WiMedia" and "WiMedia / 60GHz" multi-band multimode systems. Conclusions are drawn about which would be most productive strategies to pursue. These may be developed in subsequent tasks during EUWB WP5.

3 Characteristics of Wireless Links

This section describes the different radio technologies, protocol specifications and the prior art of heterogeneous networks.

3.1 General Characteristics

Wireless technologies vary considerably in terms of their capabilities. These capabilities are designed with the specific intention of addressing an application use case and may be influenced by a greater or lesser extent by physical constraints and regulatory acceptance. For example range may be restricted by absorption by water vapour, such as in the case of 60 GHz, or specific restrictions on the level of radiated power of a transceiver due to spectrum regulation, such as in the case of WiMedia. In addition, consideration of the effects of the rate of absorption of the RF energy by the human body may be a significant issue, such as is the case where the application use is a handset or headset.

A number of basic characteristics are generally considered to define a RF technology at a basic level, including power consumption, range and throughput. Table 1 compares a variety of common attributes, to demonstrate the choice of technologies for use within a hybrid radio system.

	Typical Range (up to)	Operational Frequency	Typical Throughput	Max PHY Rate (encoded)	Energy consumption (mJ/Mbit)
60GHz [25]	10m	60 GHz	2 Gbps est	6.3 Gbps	5 est
Bluetooth 2.0 (+EDR)	100m	2.4 GHz	3 Mbps	3 Mbps	100
802.11b	35m	2.4 GHz	5 Mbps	11 Mbps	75 - 100
802.11g	35m	2.4 GHz	20 Mbps	54 Mbps	15 - 20
802.11n	70m	5 GHz / 2.4 GHz	100 Mbps	600 Mbps	30 - 40[1]
WiMedia[6]	10m	3.1 - 10.6 GHz	150 Mbps	480 Mbps	1.5 - 2
Bluetooth HDR [4]	10m	7.4-9.0 GHz	170 Mbps	480 Mbps	1 - 2

Table 1: Comparison of WPAN Radio Technologies

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1 Power consumption figures for 802.11n have not been fully analysed by TES, however at 70m range (and perhaps up to 160m outdoors) we believe power consumption is likely to be significantly more than WiMedia UWB and 802.11g

In addition to the common attributes shown in the table there are a number of further features which may influence the choice of radio technologies in a hybrid radio system. For example the WiMedia specification provides an interface for range detection and Bluetooth has mature features for device enquiry and discovery.

3.2 Characteristics of Heterogeneous Links

This section discusses the features and attributes of heterogeneous links and how these can be applied to various use-cases.

3.2.1 Point to point only

The study of QoS across wide area networks requires the interoperation of applications, bridges and routers. Provision of services across multiple hops in networks lies beyond the scope of this document. Additionally, QoS on broadcast transmissions is also fraught with theoretical difficulties. As a result, this document is restricted to consideration of point-to-point connection oriented communications.

3.2.2 Temporal Variation in Channel Capability

The optimisation of heterogeneous communication between devices requires careful study of the nature of the connections[16] and also of the traffic[23]. The variability in the required data flow, the size of the data packets, the degree of buffering and variations in the radio signal quality all have an impact of the eventual quality of the link.

3.2.3 Characteristics of Data Streams

Data streams can be characterised according to "time taken to start transmitting", latency and throughput [24].

3.2.4 Characterising Data Requirements

Control messages are short and require low latency with high availability. Data messages on the other hand require high rate intermittently. The protocols which are used provide robustness, and may vary the link speed and acknowledgement policy in order to improve the reliability of a stream.

Due to the use of different protocol stacks in each radio technology it is likely that BoD control messages will continue to be sent on that channel even when a high data rate channel is available.

Indeed mixing small packets control packets, with large data packets can lead to reduced throughput [24].

3.2.5 Flow Control between the Layers of the Stack

The "leaky bucket" algorithm is frequently used in protocol stacks to reduce the amount of resource required to provide a reliable link of a given capacity. It reduces the required resource further down the stack, from the maximum throughput, down to something closer to the average throughput. It does this by buffering the data. As a consequence of this there is a possibility that on occasion the buffers will fill. It is therefore important that the higher layers can be made aware of this so they can adjust their requirement, request more resource or downgrade gracefully. Such flow control can either be course "the buffer is full stop sending" or sophisticated "growing and shrinking buffers" or abdicate responsibility to the sending entity "here is how full the buffer is".

3.2.6 Flow Control between Devices

In more complex systems the sender and receiver may have different levels of resource, also the data generating application and the data consuming application may be imbalanced. It is therefore important that any layer which carries out buffering considers peer-to-peer flow control, or at the very least negotiating throughput capabilities to eliminate such a possibility (at the expense of flexibility).

3.2.7 Bandwidth Brokering

When multiple applications are using a particular channel it is necessary for each of them to request resource and for the resource allocation to be arbitrated. The policies of such a broker are outside the scope of this study. However, such a broker generates the configuration messages for the lower layers of the stack, so in the context of the architectures proposed in this study the *bandwidth broker* is considered to be a primitive configuration entity.

3.2.8 Bonding

Bonding is a means by which packet fragments from a single stream can be transmitted over multiple channels and then reassembled into a stream at the far side. TCP/IP does something similar at a higher level, sending packets over multiple routes. It does, however, use significant overheads. Simpler methods with a lower overhead are considered for point-to-point architectures.

At a point-to-point level it can be achieved much more simply by a simple wrapper on the fragment data load. This labels the intended stream and can be complimented by a multiplexer providing a lock-step reassembly. An example of a protocol providing this facility is MLCP within the PPP stack[17].

3.2.9 QoS

QoS at the application level provides a description of the data which is to be transmitted in terms of rate and latency [20]. This is translated into hard requirements for the service provided by each layer, as the data passes from stream to link, to channel and then back again. As each layer is configured it has to negotiate with its peer entity on the other device. The configuration data and the negotiation protocols can be nuanced when resource utilisation and efficiency are to be optimised.

Latency can result from the sharing of the available bandwidth or the method of that sharing.

3.2.10 Adjustment of Provision

Typically, each layer of a protocol stack is responsible for maintaining an understanding of its utilisation and throughput in order to allow it to make reasonable requests of the entities below it in the stack, and to provide bandwidth on demand (BoD) where appropriate.

Whenever there is a requirement to change provision, the layer must ensure that its peer entity is made aware. The layer above is requested to stop sending further data, allowing all outstanding data to be sent and the layers below cleared down where appropriate.

3.2.11 Handling failure

The nature of wireless communication means that failure of a link as a result of interference, misalignment or moving out of range is a frequent occurrence. Therefore it is important that this should not result in catastrophic failure.

3.2.12 Physical Differences in Suboptimal Environments

Different technologies operate over different frequencies and using different physical encoding and detection. Some technologies are more robust in terms of handling multiple paths and reflections caused by obstacles. The UWB radios are more robust in noisy environments and handle reflection well. The 802.11 standards have a greater range than UWB but do not handle electromagnetic noise so well. 60GHz is more robust to the effects of co-channel interference (CCI) due to its directional nature.

3.3 A Look at Particular Use-Cases

This section looks at how BoD and QoS requirements might be met by the hybrid radio link in real life use cases [11].

3.3.1 Portable Multimedia Device Synchronises with a PC

Portable devices running on battery power require low power usage as a priority.

When wireless services are required, power savings can be achieved using a hybrid radio system through the ability to use low data rate standards, and ramp up to high data rate when both available and necessary. For example, consider the case where a handheld media player is using Bluetooth to provide connectivity to wireless headphones, The Bluetooth radio can be used to provide the necessary service discovery records, including channel and protocol version, that can permit a connection to be configured to a PC for data transfer. The handheld device, when required by the user, then provides a higher data rate WiMedia UWB radio to initiate the transfer of the media files from the PC to the media player in a fast and power efficient manner.

3.3.2 Back Up Audio on a Video Call

Audio might continue over Bluetooth when the high definition stream of a video phone call is temporarily lost due to a change in the operating environment. The video is restored when conditions allow.

In order to achieve this, audio could be sent on both Bluetooth audio and as multiplexed data on the high definition stream. The application would pick which stream to take audio from based on the availability and quality of the link. The application would not need to understand or control the hybrid link.

3.3.3 Aeroplane Cabin

A wide variety of uses for wireless technology within aeroplane cabins are anticipated. These range from cabin crew call buttons, through streaming audio, to provisions of in-flight entertainment. An example would be that the passenger seat-back entertainment system might run a slim client which used a web browser running over Bluetooth for entertainment selection, in-flight radio and headphones, before switching on its WiMedia radio to receive the in-flight movie. This would provide advantages of lower power consumption, in addition to removing the requirement for data cabling.

3.4 Characteristics of Platforms

There are many consumer electronic devices in the market place which support one or more short range WPAN radio technologies. Typically, Bluetooth 2.0 and 802.11b/g are the only well established WPAN radio technologies that are currently found in widespread use.

802.11n products based on Draft 2 of the standard are available now and have received generally positive reviews both in terms of increased speed and range and compatibility with older Wi-Fi products. However, the standard is not anticipated to be fully ratified until March 2009 at the earliest.

WiMedia devices are starting to penetrate the Wireless USB PC peripheral cable replacement market, and can also be found in some highly specialised video streaming products. The technology is, however, still seen as maturing and much work is required to achieve the performance expectations in terms of application throughput that were claimed to be achievable at the conception of the standard.

Products based on 60GHz radio technologies are not expected for another few years. There will be competing standards in this area, and although the ECMA standard [5] has now been released, prototype devices are not currently readily available, although academic work in this area is hopeful [25].

4 Proposed Combinations of Wireless Technology

The following proposals are designed in order to provide the most flexible use of heterogeneous networks in an application scenario where application level throughput rates are in excess of 100 Mbps and a specified quality of service is required to guarantee reliable data transfer.

Such a requirement should be provided in a way which uses the most flexible and mature protocols available; where those protocols are widely adopted and likely to provide interoperability on a wide range of platforms with a wide range of applications. Where public domain implementations exist, these should be taken full advantage of.

Table 2 provides references to the protocols mentioned in the following analysis along with their purpose and the relevant standards body.

Protocol	Purpose	Where defined	Standards body
PPP	A protocol stack providing point to point communication (i.e. data link layer)	RFC 1661[15]	IETF
NCP	Protocol to provide control between network layers	RFC 1661[15]	IETF (this is implemented as part of any OS supporting QoS over TCP/IP)
RSVP	Protocol to communicate with a Bandwidth Broker	RFC 4860[21]	IETF (this is implemented as part of any OS supporting QoS over TCP/IP)
DiffServ	Protocol to configure a packet scheduler	RFC 2475[20]	IETF (this is implemented as part of any OS supporting QoS over TCP/IP)
BACP	Protocol to configure logical links	RFC 2125[18]	IETF
BAP	Protocol to control LCP	RFC 2125[18]	IETF
LCP	Provides translation of logical links to QoS streams	RFC 1570 [13]	IETF (a FreeBSD implementation exists)
HDR Bluetooth	Provides PAL, between an AMP HCI Interface and the MAC/DME	proposal for Bluetooth Sig members only[4]	Bluetooth Sig
WiMedia MAC	The medium access layer for WiMedia UWB	ECMA-368[6]	ECMA
60GHz MAC	Provides an 60 GHz MAC interface suitable for an HDMI PAL	ECMA-387[5]	ECMA
MLCP	Multi-channel bonding at data link level	RFC 1990[17]	IETF

Table 2: Protocol Summary

4.1 Provision of Bandwidth on Demand

There are two main types of bandwidth on demand;

1. Fine - this is where QoS is controlled with a high degree of granularity by the higher layers under requests from the applications.
2. Coarse - this is where the stack detects saturation and brings up a channel to fulfil the throughput requirement.

Fine BoD requires that the applications are QoS aware and are able to communicate their requirements to an arbitrator (the *bandwidth broker*). The *bandwidth broker* then requires a high degree of control over the streams and the configuration of the resulting streams.

Coarse BoD on the other hand merely requires that the stack understands the current throughput and is capable of autonomously bringing up a further physical channel.

There are two main roles for BoD provision;

1. Power saving due to radio sub-systems being switch off when their throughput is not required.
2. Multi-channel bonding.

In order for the radios to remain off when not in use it is necessary for both sides to remain in contact via a second means of communication. This is generally achieved by tunnelling the control protocol for the dormant channel over another available channel. This method is referred to as Out Of Band signalling.

The diverse nature of applications and their requirements mean that it is impossible to provide a generic configuration which would be suitable in all circumstances. A common basic configuration is where physical channels are set up and dropped according to buffers filling and inactivity timers respectively.

4.2 The IETF Architecture

The Internet Engineering Task Force (IETF) is a large open international community of network designers, operators, vendors, and researchers concerned with the evolution of the Internet architecture and the smooth operation of the Internet.

As part of this work the IETF has developed an architecture for point-to-point communications. The IETF protocols are an elegant and proven solution, with facilities for QoS and BoD.

The IETF link level architecture integrates readily with the TCP/IP stack[14]. Its allowance for QoS over heterogeneous networks was originally developed for AODI (Always On Dynamic ISDN). As such it is a proven technology.

The architecture provides similar facilities to the Bluetooth *L2CAP* in terms of data transfer but is overall leaner in terms of functionality and it better suited to the high speed data transfer aspect of a hybrid radio system.

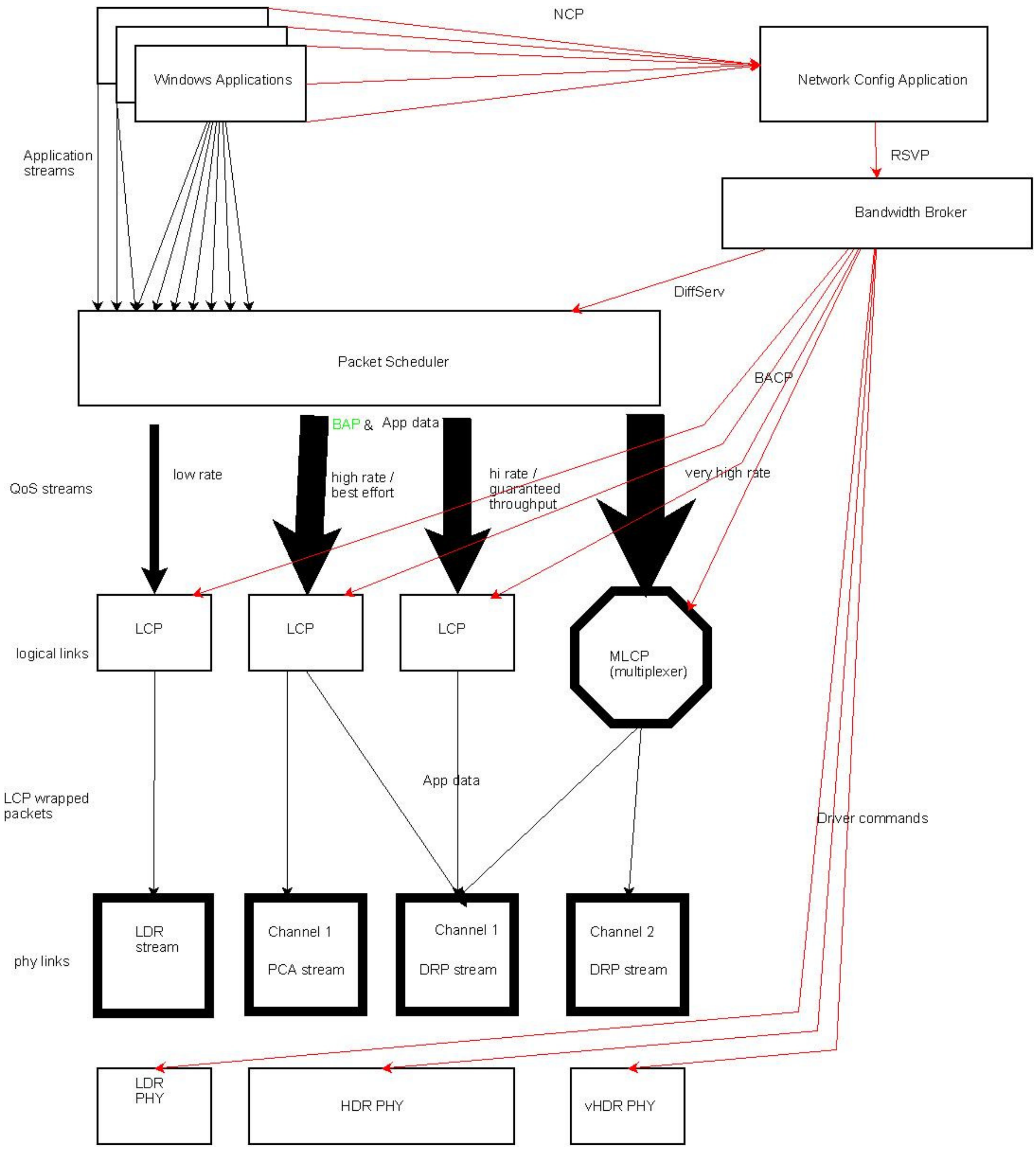

Figure 1: Proposed IETF architecture

The proposed architectures take as their model the IETF point-to-point (PPP) Architecture, as defined by reference [12]. However, in the interests of backwards compatibility, reuse and avoidance of functionality duplication, the facilities of the current stacks are used where appropriate.

Descriptions of peer-to-peer (as well as layer-to-layer communications) are described in the RFCs. As the RFCs were themselves modified for BoD, the observations and protocol modifications in them indicate the additional requirements which are made on such protocols.

The failure of a link is handled in the IETF architecture by the entity at each layer monitoring utilisation and throughput. When it deems it to be appropriate to drop or adjust, it informs the layer above, and negotiates taking down the link with the peer. Often the layer above adapts rather than tearing down, but this is implementation specific.

Where BoD or channel bonding is required the entity maintaining the logical links must exist on the host.

4.3 Possible Architectures for the Identified Hybrid Systems

This section takes the form of what services do we want to provide and how they are provided by the PPP stack and Bluetooth stacks.

The BoD capability of the PPP stack was developed as part of an initiative called AODI. This was for general internet use over ISDN, as an alternative to analogue dial up. As a result there is little or no account of the time it may take to initialise a hybrid radio system. An extension of the extended flow specification called "Bring up latency" should be provided. This is to allow applications with low SDU latency, but unimportant start-up time, to use BoD (e.g. video conferencing). It allows other applications with more sudden transfer requirements to decide whether to keep the link up or not.

4.4 Combination A : Bluetooth HDR / WiMedia

Figure 2 shows a hybrid radio system consisting of Bluetooth and UWB radio sub-systems, thus supporting the HDR Bluetooth architecture, with PPP present.

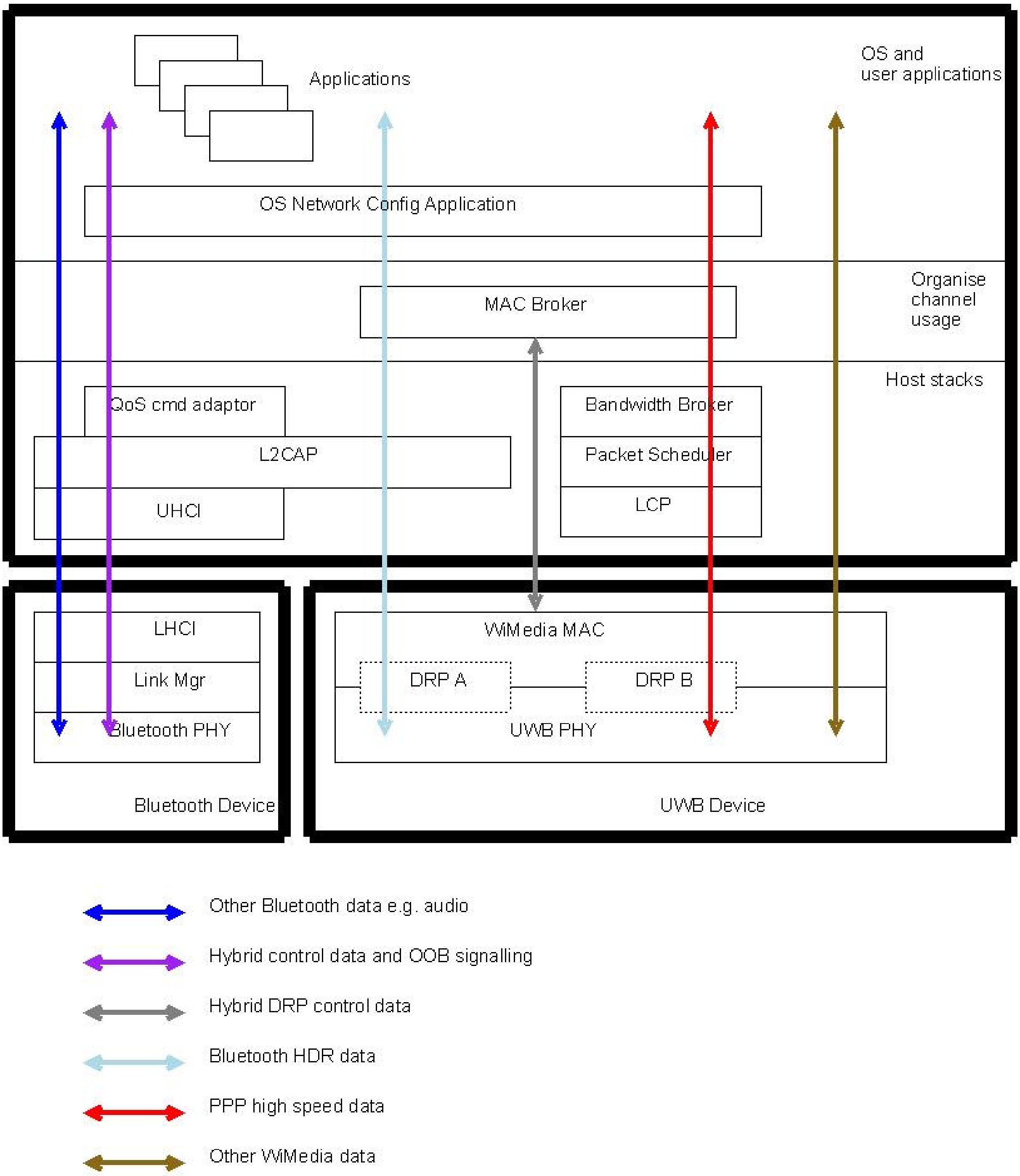

Figure 2: Bluetooth / WiMedia Hybrid Radio System

L2CAP provides a number of the facilities available in components in the PPP stack. These facilities include fragmentation/re-assembly and multiplexing. As a result there is no intention of having HDR Bluetooth and PPP share the same DRP at the same time. The two host stacks can use the same radio via the convergence layer.

The PPP stack is designed to handle connections over multiple physical devices. As the packet scheduling algorithm requires careful consideration if the links are not identical, it is unlikely that this would be available in any early implementation. However, it is possible that this will be required later and so design decisions should take it into account.

The *DRP broker* decides on the essential split of the UWB medium between DRP A (Bluetooth) and DRP B (PPP stack). The balance between these is a QoS issue for the data on the streams. The configuration of this component may be carried out at start up for simplicity, or a more complex dynamic configuration application may be required.

The PPP stack provides for client applications requesting that a logical link be terminated. If no other logical links are using the associated physical link. It also allows for the termination of a physical device if required. The policy for such an action is generally encoded in the *bandwidth broker*. However in this system that functionality would have to be moved up to the *MAC broker* (as this is the common component of the two stacks).

The QoS adaptor would convert the RSVP QoS commands in the best way possible for the radio protocols in use.

As the DRP Broker will have to know whether Bluetooth wants to use UWB its task is greatly simplified. The higher layers and applications will also require less modification for this purpose.

L2CAP has one significant problem for use with hybrid radios and that it has no concept of a logical links for which the physical transport is shut down. BoD requires that the application should not have to carry out discovery and renegotiate the QoS parameters of the link when the additional channel comes back up. The specific parameters of the physical channel have to be renegotiated however.

This means that the lower layer will have to be driven via the state machine of the logical transport. The issue being that when a logical link returns to this partially closed state, entities in the *L2CAP* (the layers further up) should not clear down in the same way as if an event suggesting a full closure of the link had been required. They should, in fact, continue to make the stream available.

The modification required to Bluetooth stack is to modify *L2CAP* to provide a CREATED_BUT_CLOSED state, such that a logical link can exist without the channel being open. This is equivalent to the Network-Layer Protocol phase in RFC 2125 [18]. It is essential that any such additional state and associated events should not impinge upon the states and events as defined in the Bluetooth specification, as this may lead to non-compliance. It is obvious from the RFCs, and the BoD requirements contained therein, that this modification of the state machine will prove necessary.

The upper layers still need to know if a link has fallen back into CREATED_BUT_CLOSED state so that they can decide whether to hibernate or power down sub-systems of the hybrid. This would be achieved by a new message from *L2CAP* to the *DRP Broker*. The decision would also be based on the use of the device by the other stack.

The *L2CAP* logical link entities should also have a configurable inactivity timer. This would be configured to drop the link back to CREATED_BUT_CLOSED if it detected insufficient traffic and there was no requirement for a low "bring up latency". This would generate an event for the upper layers so they would be aware of the changed characteristic of the link.

It is assumed that a single physical link, referred to as channel in *L2CAP* nomenclature, is used to provide a multi-link bundle (i.e. all links on a given AMP use the same reservation). This is used to remove the need to negotiate bandwidth between physical links on the same AMP controller (as well as with the other device, as well as between logical links on the same physical link).

If it is required that an application should switch data links between controllers while the link is active, this would be best supported by switching logical links between physical links on different controllers, rather than bringing up and tearing down physical links. In particular it would remove the issue of queue flushing at the various levels of the stack.

As *L2CAP* is concerned with the maintenance of logical links and this is required even in the absence of the physical link (and possibly the controller is powered down) it is necessary that *L2CAP* would have to be kept on the host. This requires the use of the HCI interface.

Although *L2CAP* is responsible for the maintaining the logical link it is not aware of the data requirements of the layers further up the stack. It falls to the *bandwidth broker* to understand the conflicts and changes in data flow and configure the *L2CAP* accordingly.

As the *bandwidth broker* has these responsibilities a system might be conceived whereby the *bandwidth broker* could set up a new logical link on the other controller then gracefully reconfigure the *packet scheduler* to transfer application data to it and tear down the old one. This would require modifications to the *L2CAP* messages. That is a message from the logical link *L2CAP* to complain that its link is saturated and suitable flush commands.

A *bandwidth broker* (for example on MS Windows one supporting RSVP) is responsible for ensuring suitable QoS and priorities are negotiated for each application within the limited resources.

A *packet scheduler* fragments/defragments packets and queues/buffers the data to provide the necessary latency. There has been a good deal of research carried out on packet scheduling but for most purposes a naive scheduler with carefully configured applications works best.

It is assumed that the channel is either a soft DRP or a fixed DRP of suitable size directed by the *bandwidth broker* and negotiated with the peer device.

In order to support the use of 'standard' MS Windows *bandwidth brokers* it would be necessary to deploy a "diffserv" to "extended flow specification" adaptor to allow the direct use of Bluetooth streams to provide the required QoS configuration. Although straight forward in principle there would be many scenarios and compatibility issues to overcome to achieve its full potential.

Bonding is provided by functionality in *L2CAP* however bonding a pair of asymmetric links into a single data flow is fraught with problems. If multiple links with different throughputs are being used to speed up data transfer then IP is the correct layer to achieve this.

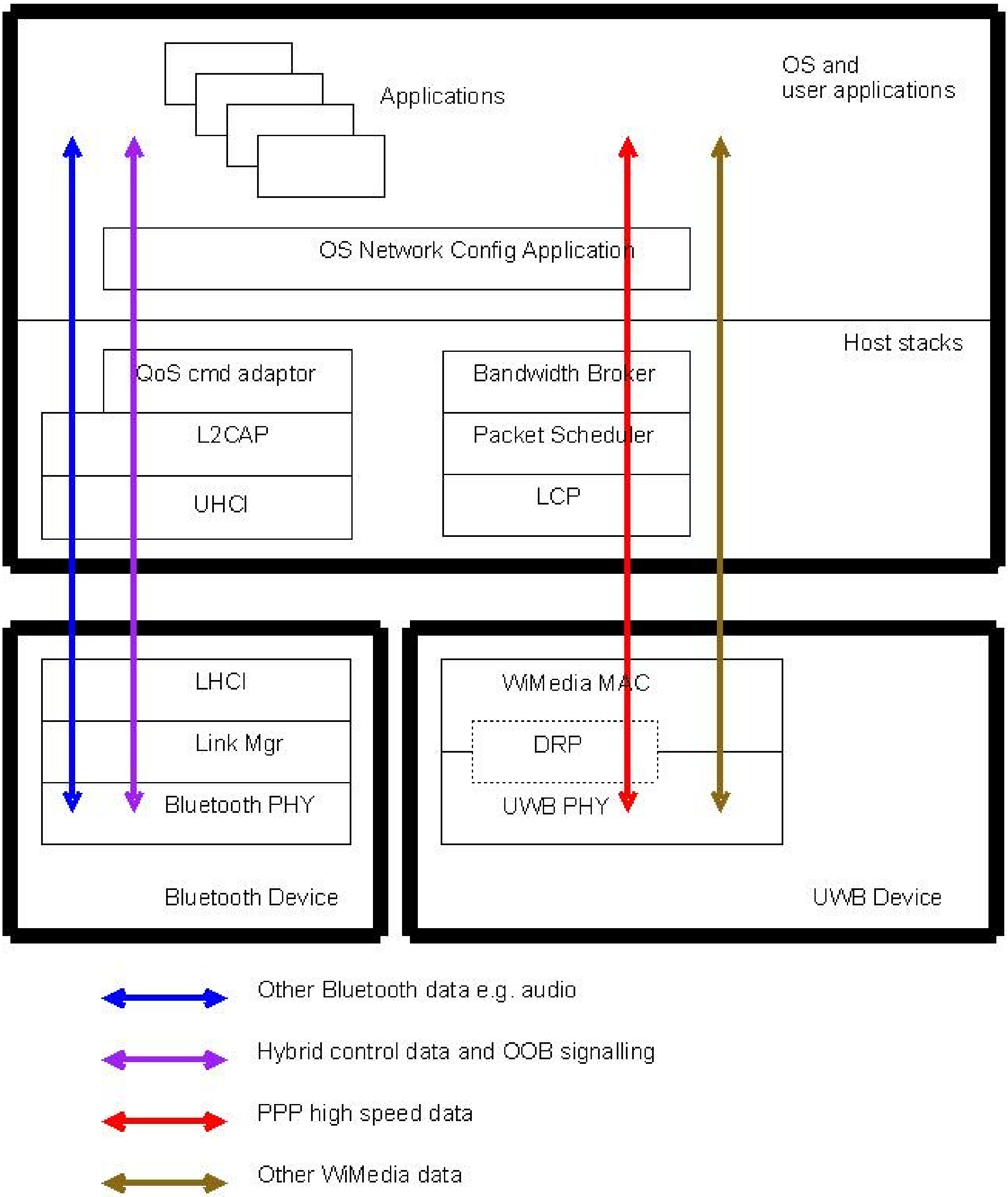

Figure 3: Bluetooth / WiMedia Hybrid Radio System (no Bluetooth HDR)

A hybrid system with Bluetooth 2.4GHz and a single UWB/PPP would simplify development considerably, and would demonstrate hybrid radios acceptably. The removal of the MAC broker and its function of handling the DRP contention between the UWB subsystems would simplify QoS translation considerably. As the hybrid radio would not have to allow for the possibility of other devices wishing to communicate with this device by using the UWB radio for Bluetooth HDR, it would also allow the UWB device to operate on band groups other than that approved for Bluetooth

HDR. It would also be directly portable to 60GHz (with the exception of service discovery which could be added as an Application Specific Information Element ASIE to say which protocol is available and on what channel).

4.4.1 Key differences

A distinction is made between provision of HDR Bluetooth and the discovery and provision of a high speed TCP/IP link, with QoS, over WiMedia. The former is of use primarily for the piconet and the latter for communication with a WAN.

4.4.2 Rate adaption comparison

Translation of one QoS paradigm into another, and the use of available resources to meet those requirements are a non-arbitrary task. This is exacerbated in the case of rate adaption.

The Pulsers II work [7] includes algorithms for DRP adjustment to meet the Bluetooth rate adaption requests. It would be expedient to reuse this work

4.4.3 Exposing WiMedia Capabilities

The service discovery section of the Bluetooth specification already covers the application service (e.g. colour laser printing). It also has coverage for internet based network protocols. What it lacks is a definition for the WiMedia radio and the lower level network protocols used by that device.

4.4.4 Bluetooth Service Discovery Optimisations

Application level services will have to indicate whether they can operate over the various radios, and if so using which protocols. The use by the application level of the sophisticated and mature service discovery features of Bluetooth is thereby maintained.

These are however comparatively small modifications in comparison to having to add the configuration options for the WiMedia radio.

4.4.5 Obtaining Practical Data Characterisation

Each link will need to have its data transfer characteristics detected, the higher layers will require access to the adjustment and feedback features. The IETF specifications stick to a straight forward delta of good packets and bad packets[16]. Until there is strong evidence to the contrary this may be assumed to suffice and the onus placed on the use of this data in the higher layers to adjust accordingly.

For the purpose of deciding which links to bring up it would be necessary to know how long this takes. Ideally this information should be collected rather than hard coded as the circumstances of the environment may have an impact on this.

4.4.6 Link Utilisation and Contention

Some method for utilisation, prioritisation and contention must be provided. So an application can ensure that a minimum QoS in terms of rate and latency are possible. Further to this, in the case of failure a re-evaluation and reallocation of resources based on importance can be triggered by the upper layers.

The IETF specification is carefully constructed so that the command can be sent on the slower OOB stream without interfering with the faster in-band data transfer. It has been observed that mixing these two data streams can limit throughput [23] and mutual queuing of the two streams causes slowing of the traffic.

4.5 Combination B : WiMedia and 60GHz

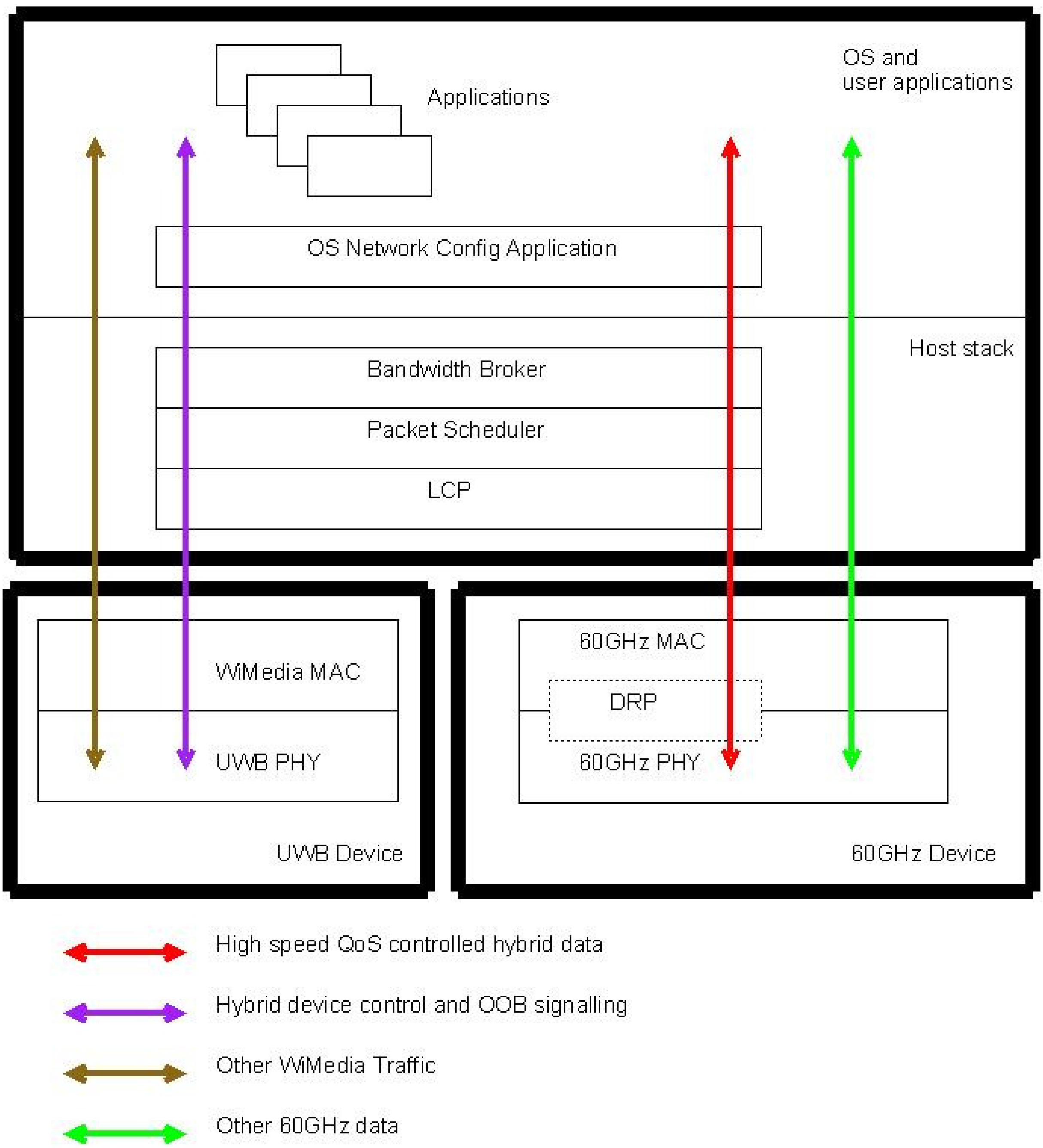

Figure 4: 60 GHz / WiMedia Hybrid Radio System

In this variation the two subsystems are able to make use of the same host stack. This would reduce code size considerably, simplify QoS operation still further and allow opportunities in the future for channel bonding.

4.5.1 Provision within the OOB Messages

The ECMA387 specification for 60GHz PHY and MAC contains IEs covering device discovery and also the detection and adjustment for variations in link quality.

ECMA387 [ref [5] section 18.2] includes a section on the protocol for a convergence MAC using "out of band" signalling over 802.11g. This is to allow the 60GHz radio to be adjusted optimally without fear of losing connection.

Rather, than integrate this set of non-WiMedia compliant IEs, with the WiMedia stack for this specific hybrid combination. The simplest approach would be to wrap and place these IEs into, what is known as, an Application Specific IE within a WiMedia command frame. If this was to use the same framing as the ECMA LCP then the necessary information could be passed up through the MAC to the *bandwidth broker* with little or no change to the generic lower levels of the PPP stack [19]. The *bandwidth broker* (which is common to both radio stacks) would then be in a position to action the necessary changes to the 60GHz antenna configuration.

4.5.2 Modification for Dormant Channels

The aim of OOB signalling in ECMA387 is to provide, as far as possible, a continuous service (which is a valid and fruitful use of it). However the requirements of BoD vary from this in that they require the maintenance of dormant channels. There are three levels of device dormancy which might be supported -

1. Hibernation (no transmission) - this equates to 'parked' mode in Bluetooth
2. Radio off (no transmission or reception)
3. Device powered off (not just the radio, but the processor and transport connection etc.)

The addition of subclasses of application specific information elements on the WiMedia beacon could be used as a means of communicating information about the 60GHz link OOB. An example would be an IE to cause indefinite dormancy and waking of the 60GHz radio. Another example would be an IE to support a channel change OOB, when the device is dormant (so that the dormant device knows where the other device has moved to and can rendezvous with it).

In general the more that is powered down the longer it would take to come up again. In order to improve latency of links, where short term savings are appropriate, hibernation might prove useful also.

4.5.3 QoS Optimisation

There is much optimisation which can be carried out in the *bandwidth broker* and the *packet scheduler*. These are at higher layers than the subject of this study. They either involve a more intimate knowledge of the application layer requirements, active negotiation or the use of QoS protocols such as RSVP .

4.5.4 Obtaining Practical Data Characterisation

As the OOB signalling definition in ECMA 387 are for the purposes of antenna adjustment and other fine tuning of the 60GHz channel, they do provide facilities to monitor the link.

4.5.5 Link Utilisation and Contention

It is quite possible that the QoS demands of all the applications will exceed the capacity on the physical medium. Some method for utilisation, prioritisation and contention must be provided. Further, in the case of channel degradation (or improvement) a re-evaluation and reallocation of resources based on importance can be triggered. In such a case only the necessary applications need be impacted.

4.5.6 Likely Path Split

The nature of messages that are sent out of band is such that it is unlikely that there would be any advantage in moving them to a faster channel. They are intermittent, short and usually concerned with checking the status of the fast link.

Mixing small and large packets has a strong negative impact on throughput [24] so this is undesirable.

The bonding of data streams on links with different speeds is problematic in terms of scheduling, multiplexing, reliability on packet loss and throughput. Therefore it would be left to the application layer to address additional low rate streams directly to that interface. This has the advantage of backwards compatibility. An example of this is provision for SCO (Synchronous Connection Oriented) links for voice over Bluetooth.

5 Potential Prototype Platforms

This section considers the two architectures described in section 4 and discusses the implementation of modifications to the current standards in order to allow them to operate with QoS and BoD.

5.1 The Bluetooth / WiMedia Hybrid

This section covers a hybrid device with both a Bluetooth (2.4GHz) radio and a WiMedia UWB radio.

5.1.1 Integration with Operating System QoS Software Components

In order for the hybrid radio device to be used optimally by a host PC, it would necessary to integrate the supporting protocol stack with the operating system's QoS software components. All current versions of the Microsoft Windows operating system and Unix derivatives use the RSVP protocol [14] to request QoS.

5.1.2 The PPP on WiMedia Solution

Although PPP is a proven protocol for high speed networking and BoD, there is not a FreeBSD implementation with all the features required. Therefore an implementation will either have to be written or licensed.

5.1.3 Upgrading Bluetooth Service Discovery

As there co-existence of other devices on the frequency and the utilisation of other PALs there is little point in describing the link as link quality, DRP availability, speed and other parameters that are exchanged by beaconing (also see following point concerning persistence of data). Therefore the concept of passing OOB beacons (as proposed for the 60GHz OOB signalling [5]) can be rejected for this configuration.

The Bluetooth Service Record will require a separate hybrid radio service class. This will provide other Bluetooth radios with all the information required to configure and connect as a hybrid radio.

There are four attributes which have to be made available concerning the WiMedia radio sub-system of the hybrid radio descriptor.

1. The current operating channel of the WiMedia radio.
2. Available bands/band groups supported by the WiMedia radio, to reduce the time taken to scan and discover one another on a limited number of supported bands.
3. Which PPP protocols are supported and in what version. This will have to include any Vendor Extensions [19] added.
4. The EUI-48 of the WiMedia device as this allows the beacon of the other device to be recognised i.e. the hybrid devices correctly paired.

5.1.4 Persistence of data

As the negotiation between two MACs is already handled through the exchange of information elements when beaconing, the most expedient course of action is for the two WiMedia radios to synchronise with one another, negotiate a reservation and then allow the agreed parameters to be stored persistently in a higher layer while the adaptor is powered down. This would be best handled by the *Bandwidth Broker* as it is responsible for deciding when to power the radio off and on.

In the case when the radio comes back up it will have to resynchronise with its beacon group. In the case it is unable to contact the other device it will have to scan and renegotiate the PHY parameters as the medium has obviously changed.

Unfortunately, it will not be possible to assume the same DRP, as there will be no hibernation anchor to hold off the other devices using the medium.

5.2 The WiMedia / 60GHz MAC

5.2.1 Key differences between 60GHz MAC and WiMedia protocols

The 60GHz specification [5] bears many similarities to the WiMedia specification [6], These similarities take the form of the basic form of super-frames, beacons and IEs. Where they differ is in the provision of three different types of device (with respect to beaconing frequency), and in the provision of additional IEs for the adjustment of the antenna.

Although there are many similarities between the 60GHz and the WiMedia specifications, both the syntactic and semantic nature of each IE will have to be analysed and compared.

The HDMI section of the 60 GHz specification is a highly specific application use case with no relevance to a generic QoS scenario.

5.2.2 The Undesirability of a Common Codebase

As the standards for WiMedia and 60GHz medium access controllers bear many parallels it is tempting to consider the possibility of a common code-base.

Whenever considering a common code base it is worth considering a number of simple questions;

1. Are the differences small enough that they might be considered as versions?
2. Are the areas of difference likely to result in well defined self contained code (or are there likely to be sections of code interleaving)?
3. Is a bug fix for one version likely to fix a bug in the other, or result in a problematic change in behaviour in the other?

The idea of a common WiMedia / 60GHz codebase fails on each of these points. The conclusion is that there is little benefit in maintaining an actual common code base.

It is, however, expedient to base the 60GHz code on the WiMedia code and to impose some procedure to keep them in tandem where appropriate (to ensure reporting of bugs to both code bases and allowing the porting of new features, for example).

It is also likely that prior to inter-operability testing, bootstrapping the 60GHz stack from the WiMedia stack would prove useful. By this it is meant that each subsystem of the WiMedia stack be replaced piecemeal. This would make full use of the convergence architecture and, hopefully, allow a demonstration of a working, though non-compliant, system.

5.2.3 . Service Discovery on WiMedia (for integration with 60GHz)

Although there are Information Elements defined for service discovery, the content of those Information Elements is not defined. It must therefore be assumed that the WiMedia devices will have a compatible (as yet undefined) service discovery mechanism.

Such a mechanism will have to include additional information such as which PPP protocol versions are implemented at the various layers and any vendor extensions[19]. A variation of Bluetooth Service browsing is a candidate for such a mechanism.

The EUI of the paired 60GHz device will have to be recorded with the hybrid radio element of the service information.

Once the service discovery mechanism has completed, and presuming that the application services are compatible, it will be necessary to discover the 60GHz radio and its MAC capabilities. This can be achieved with the same OOB protocol as proposed in the 60GHz specification for 802.11g OOB signalling. In particular, the OOB antenna adjustment and the MAC capability interrogation would be invaluable in setting up the link.

The suggestion in the 60GHz specification is that prior to the powering up of the 60GHz radio and it starting to beacon (or during parking), that beacons can be sent OOB in order to obtain further information. There is doubt as to the efficacy of this method since by far the simplest way to exchange this information is to have the two devices beacon briefly and retain the information in a persistent store.

5.2.4 A Possible Development Strategy for 60GHz Software

It should be possible to develop the new 60GHz MAC software on a wired WiMedia setup. This would allow the required logical modifications to be made to the upper part of the MAC and tests to be developed without the added uncertainty of new hardware. Integration of the 60GHz hardware would therefore be eased. This would also encourage the two software streams to remain in tandem.

5.2.5 Limited WiMedia Platforms

Limited availability and variety of WiMedia hardware limits the possibilities for co-existence testing and also any practical demonstration.

5.3 Higher Layer Considerations

Regardless of the exact form a hybrid radio would take the higher layers of the stack have to take account of the nature of the link they are using.

5.3.1 Brokering Bandwidth

Most of the envisaged uses for the heterogeneous radio systems are limited to individual high data rate streams.

Obviously, it is possible to have multiple applications requiring more bandwidth than that which is available. However, issues such as over-subscription lie outside the scope of the element of the stack covered in this document.

5.3.2 Requesting Capacity Check

Spatial variations such as medium saturation, climatics and location can vary the capacity available. Indeed they may result in different profiles being suggested by the technology at either end. The higher layers which decide which channels to have enabled should be able to request capacity updates. For example where another user of the medium ceases or reduces its usage it should be possible for the host to rationalise the connection if that is desirable.

5.3.3 Routing and Meshing

Routing and meshing between nodes lies beyond the scope of this document as these are higher order functions. This document only covers point-to-point connections. Whether those connections are used in an ad-hoc, infrastructure, or other manner, is for the higher layers to handle.

5.3.4 Application Quality Fallback

The nature of wireless links is such that the quality of the link can be suddenly and significantly reduced (even lost). It is therefore important that the applications are able to handle such a loss without degrading quality beyond what is necessary. This might involve varying the codec, increased use of buffering or reconfiguring its QoS requirements.

6 Conclusions

There are several different stacks involved in the implementation and support of hybrid radio platforms. The host and different radio technologies each have their own historic protocols, and integration between them is often not an arbitrary task. This is particularly the case where we want to develop a consistent approach for several protocols on the same hybrid platform.

Although the convergence layer handles use of the medium by multiple protocols it cannot account for the higher level decisions, concerning the arbitration of resource allocation. Neither can it handle the issues surrounding the decisions to shut down and bring up the adaptor, due to QoS latency of the particular applications.

Having identified existing protocols and standards for the support of heterogeneous networks, this study suggests the IETF architecture for point-to-point communications provides a suitable host framework for the basis of a hybrid radio system. The IETF architecture has been shown to provide support for connections over multiple logical links which may in turn be supported by one or more physical channels, as supported by one or more radio sub-systems in a hybrid radio system.

The IETF architecture requires several adaptations and support for some additional components in order to make it suitable for use with the wireless radio standards of our target hybrid radios. Examples of these are provision of a *Bandwidth Broker* and a *MAC (or DRP) Broker* for coordination of creation and configuration of MAC level reservations. It has also been observed that the Bluetooth HDR L2CAP layer provides some of the functionality attributed to a PPP stack, but requires some minor modifications as specified to adapt its behaviour for use in conjunction with the IETF architecture.

This study has also considered the suitability of the architecture to support potential platforms base on Bluetooth/WiMedia and WiMedia/60GHz hybrid radio systems.

The compelling use cases and complimentary features of WiMedia/Bluetooth hybrid radio system seem to make this combination extremely attractive as a potential prototype platform in WP5. The availability of a (V)HDR platform from WP7 and the existing development work inherited from Pulsers II [7][8][9] would provide a strong foundation for the realisation of the concepts outlined in this study.

The case for WiMedia/60GHz is less clear. The use cases seem less obvious and the absence of an efficient method of service discovery and connection configuration make the power and efficiency savings less clear in such a hybrid radio system. Further, there is no clear support of an ability to modify the band use of the WiMedia radio system in such a configuration, and this was seen to be one of the key benefits of the use of Bluetooth HDR due to the global acceptance of the 2.4 GHz ISM band radio.

The concept of re-targeting an existing code base for a WiMedia MAC to that which would support a 60 GHz PHY based on the ECMA-387 specification [5] was also considered. Although many similarities exist, the notion that a WiMedia MAC code base could be simply and easily re-targeted is rejected. However, it may be possible to use an adaptation model that implemented a suitable MAC for 60 GHz using a bottom up approach, starting with the re-targeting of the base layers, and building upon this to bootstrap a 60 GHz stack.

In summary, this study has concluded that;

5. The IETF architecture and the existing Bluetooth SIG specifications provide a clear framework for development of a Bluetooth HDR hybrid radio.
6. The (V)HDR platform from WP7, in combination with a COTS Bluetooth dongle, would provide a suitable development platform for a Bluetooth HDR implementation of the concepts proposed in section 5.1 of this study.
7. There is insufficient correlation of the code base of a WiMedia MAC implementation and a 60GHz MAC implementation to permit a simple migration from one to another.
8. It may be possible to use a bottom up approach that implemented a suitable MAC for 60 GHz by starting with the re-targeting of the base layers of a WiMedia MAC to bootstrap a 60 GHz stack,

It is therefore the recommendation of this study that the development, implementation and verification of the software sub-components required to support a Bluetooth HDR solution could proceed in EUWB task 5.2.2, with the integration of such a system in task 5.2.3 using the (V)HDR deliverable from WP7.

Alternatively, it would be possible to consider adaptation of the lower parts of an existing WiMedia MAC to support the features and functionality required by a 60GHz MAC in task 5.2.2, with the integration of this component with a suitable 60 GHz PHY in task 5.2.3. This could provide a development platform with limited functionality suitable for further commercialization.

This study concludes that it is unlikely there is sufficient effort and budget to develop a full (V)HDR WiMedia/60 GHz multi-band radio system development to include PAL/MAC, BB, RF within the scope of EUWB tasks 5.2.2 and 5.2.3 at this time.

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