Distributed Resource Reservation for Beacon Based MAC Protocols

Frank Leipold, Jörg Eberspächer

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Frank Leipold[1] and Jörg Eberspächer[2]

[1] Sensors, Electronics & Systems Integration
EADS Innovation Works Germany
frank.leipold@eads.net
[2] Institute of Communication Networks
Technische Universität München
joerg.eberspaecher@tum.de

Abstract. Wireless connected devices become increasingly popular in a large variety of applications. Consumer electronics most certainly is the field with the most wireless innovations in the past years; but also other areas, such as medical equipment, vehicular on-board networks or maintenance services, experience an increasing demand for wireless communication. Additionally the networks should *just work* and require as little maintenance as possible. Hence future WLAN and WPAN must be self-configuring, self-healing and distributed to provide flexible usage. Assuming a homogeneous distributed MAC protocol with a beacon based reservation mechanism, a radio resource reservation algorithm is developed to fulfil the delay and data rate requirements from the devices. It uses a game theoretic approach to achieve infrastructure-less design and still provides fair resource allocation. Changes in the radio channel, failing devices or links and mobile nodes are detected and a reorganisation of resources is calculated.

1 Introduction

The constantly increasing performance demands for wireless high speed connections is the motor to further enhance existing technologies and to invent new and innovative communication interfaces. For wireless local area networks (WLAN) several candidates have been developed in the past years. The recently approved IEEE 802.11n standard achieves up to 600 Mbits/s, by using MIMO (multiple-input-multiple-output) technology.

High data rates can also be easily achieved by using ultra wideband (UWB) as the bandwidth of more than 500 MHz provides plenty resources. The WiMedia standard [1] is capable of 480 Mbit/s with one single channel. The recently published upgrade even allows 1024 Mbit/s. This is done with one single antenna (hence no MIMO), which implies less complex transceivers.

One significant difference between WiFi and high-speed UWB is the transmit range. Due to the strict power limitations of at most -41.3 dBm/MHz for UWB, defined from the FCC [2], and mostly followed by other regulatory organisations, high data rate UWB has a typical range of about 10 meters. It also underlies more intense spatial limitations given by walls and other obstacles. This is often interpreted as a handicap of UWB, but it actually also implies two significant advantages. First it reduces the congestion in the wireless channel. For instance the IEEE 802.11b/g technology is currently often used in home applications. But the standard has only three non-overlapping channels (respectively four in Japan). Thus in apartment houses, where most flats have their own WiFi access point (AP), the channels are very crowded as the technology can achieve 20 to 100 meters transmit range even in indoor scenarios. With UWB the radio signals are almost confined to the individual apartments and the contentions for the wireless channels get relaxed. There will be less wireless systems sharing the common resources. The second advantage is the reduced risks of being eavesdropped. The attacker must be in very close proximity to successfully receive the UWB signals. Eavesdropping becomes much more difficult and the risk of falling victim to an attack declines.

Even though WiMedia is a fully distributed algorithm, without any coordinating nodes such as a WiFi-access-points, the network still has *service providing access points*, for instance a node that is connected to a LAN and operates as a bridge between the LAN and the WiMedia network to enable access to the Internet. These WiMedia (or UWB) APs do not have any special role in terms of the PHY or MAC protocol.

Using UWB for WLAN applications requires a larger number of APs. For the office scenario about each room requires at least one AP, depending on the size of the room. This makes the network management more complex. For now usually the WiFi networks are managed by maintenance personnel, but with a large number of APs to manage, this becomes a very complicated task. Several automated resource management algorithms for WLAN systems have been proposed yet. For WiMedia little work has been done on this subject. With its completely distributed algorithms the existing approaches can not be used efficiently.

In an earlier work [3] an integer optimization algorithm was presented to calculate the optimal AP placement and resource allocation plan for WiMedia networks. It is very complex and time consuming algorithm that will run during the design phase of the network. But during the operation of the network changes to the wireless channel will occur and a fast adaptation to the new conditions must be made. Depending on the size of the network a centralised optimisation may take too long. A distributed approach is preferred.

Our applications target wireless on-board networks for public transportation vehicles, such as aircraft. Cabin management systems, containing reading lights, signs, speakers, small displays, shall be connected wireless to reduce production and maintenance costs and to make the cabin layout more flexible. UWB currently is the most promising technology that provides a very robust radio channel for the aircraft environment [4], high data-rates and no licensing problems. Furthermore the network shall have self-healing capabilities and adapt quickly to failures and changes. Therefore the resource management algorithm should be distributed and enable the network to operate with the best possible configuration even when some parts are failing completely.

The network management of the public transportation scenario is not very different from an office environment or home consumer electronics. Therefore the gained results in this paper can be easily applied to other situations, where devices must be connected to service access points.

The rest of this paper is organised as followed. Section 2 describes features of WiMedia relevant to this work. Section 3 describes briefly game theory and some related research. In section 4 the distributed resource management algorithm is presented. Finally section 5 concludes this paper.

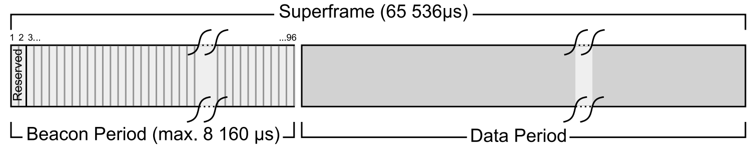
2 Unique WiMedia features

The WiMedia standard and also other possible standards that use a distributed beacon based MAC implementation, has some unique features, which are of value for the resource management.

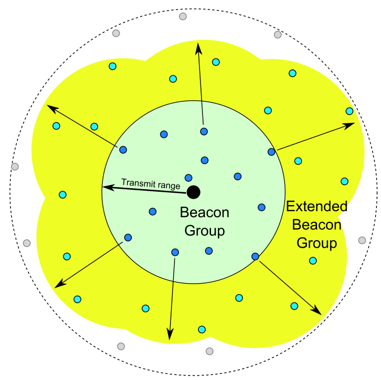
WiMedia is completely infrastructure-less, meaning all nodes have the same physical and MAC capabilities. Unlike in other common protocols there is no coordinator or MAC level access point. The protocol uses periodic superframes containing a beacon period and a data period; see Figure 1(a). All nodes allocate a beacon slot in the beacon period, regardless if they have to transmit user data or not. This slot is fix over time and changes only in rare conditions. For DRP (distributed reservation protocol) channel access the beacons are used to announce transmissions and reserve parts of the data period, the so called MAS (media access slots). Conflicts are identified early and collisions can be mostly avoided. The only collisions may occur in the beacon slot allocation process.

The beacons contain details of all upcoming transmission in the data period. This means a single node knows when a neighbour communicates with another node. This feature makes WiMedia not susceptible to the *hidden station problem* and it does not need RTS/CTS messages.

With the beaconing a hard limitation of WiMedia applies. The beacon period has only 96 beacon slots with two slots reserved for special functions. This means no more than 94 nodes must be within range on the same channel. The group of nodes within transmit range of a subject node is called *beacon group* (BG). Each node includes the members of the BG and the respective beacon slot ids into its own beacon; hence it is broadcasting this information to the surrounding nodes. Furthermore the standard also defines the *extended beacon group* (EBG), which is the set of nodes representing the neighbour's neighbours. Figure 1(b) shows the BG and the EBG of a node. A newly activated node picks a beacon slot that is not occupied by a node of the BG nor from the EBG. This rule implies that for any given node the beacon slot ids of the BG members must be unique, otherwise they would cause collisions. For the EBG members the ids can be identical, because the subject node can not listen to them, but must not transmit at the same time as it would cause collision at the node that has the subject node and the EBG-node in its BG.



(a) Superframe structure



(b) Beacon group and extended beacon group

Fig. 1. WiMedia beacon groups: Figure (a) shows the beacon period and data period of a superframe. In (b) the relation of the beacon group and the extended beacon group are shown.

The consequence of overlapping areas in WiMedia is the extension of the EBG. When a border node is within range of two APs, it will add parts of the second AP nodes to its BG, which again appear in the EBG of the first AP. Hence overlaps increase the extended beacon group size and therewith limit the maximal node density.

The beacon group size is directly related to the node density and transmission range as slots may only be occupied by one node. The extended beacon group size additionally depends on the activation sequence of the network, as for a single node the neighbour's neighbours beacon slots may be identical.

3 Game theory for resource management

For the distributed resource management algorithm presented in this work, one key feature is to have a fair resource allocation. Nodes should not act selfishness and occupy wastefully available resources. The objective of the algorithm is to maximize the overall efficiency of the network. Hence nodes must not only take their own situation into account, but also those of the surrounding nodes.

The game theory is capable of defining fair and distributed algorithms. It originates from economics in the 40's, but has also been applied to biology, engineering, political science, computer science, and philosophy. The problem is defined in a strategic game with a set of rational players. Each player tries to maximise its payoff function by choosing the best strategy and also by taking the actions of the other players into account. Usually the players strategies will result in an equilibrium, for instance the Nash equilibrium, where no player can change the own strategy without decreasing its payoff. Many different types of games have been developed: cooperative or non-cooperative, symmetric or asymmetric, zero-sum or non-zero-sum, simultaneous or sequential, just to name a few.

Game theory has been proposed for resource management in wireless networks for all kinds of technologies. For IEEE 802.11 the authors of [5] present a game to share the available radio channels. The payoff function based on transmission delay, channel access length and throughput. In [6] an algorithm for OFDM based communication is described that minimizes the transmission power, while still achieving the QoS requirements of the system. For IEEE 802.16 networks [7] presents a game definition to control the amount of bandwidth given to new connections, with respect to delay, throughput and other QoS parameters in the network.

Even though the amount of available resource management algorithms based on game theory is huge, no one handles a comparable system to that of a WiMedia network. The distributed beaconing mechanism and DRP channel access scheme is unique. The priority for a WiMedia network lies in the efficient MAS allocation. To utilise the WiMedia features a new resource management algorithm is required.

4 Algorithm

The resource management algorithm assumes APs with fix locations. Furthermore the network consists of a wired backbone that connects the APs. The APs provide the service for wireless end devices to get access to the wired back bone network.

The MAC mechanism for the WiMedia nodes shall be DRP. For the aircraft scenario DRP is essential, as it provides guaranteed resources to the end devices. The QoS requirements for end devices are defined in required data rate and maximum time delay. Assuming only one MAS is reserved per end device and taken into account the 64 ms of a superframe, the delay of an message over the UWB link can be nearly 64 ms. For applications with smaller delay requirements, the resource management algorithm must reserve two or more MAS per end device with maximum gaps between the MAS. The possible delays will be reduced.

Despite the mentioned DRP reservation scheme the network may also use the alternative channel access PCA (prioritized contention access) for non critical applications. MAS that are not completely used by the owing device can be released and used for PCA, a CSMA like access scheme. This way the unused MAS sections can still be used for applications where collisions can be tolerated.

The following two lists show input and output parameters of the algorithm:

Input parameters	**Output parameters**
• Link quality	• Channel allocation
• Devices per AP	• MAS reservation
• BG/EBG size	
• Bandwidth utilisation	
• Delay requirements	

The link quality is given in RSSI (received signal strength indicator) or LQE (link quality estimator). Both are defined in the WiMedia standard and should be accessible from the application layer.

It is assumed that an optimal configuration of the network is known. This can be obtained from calculations in the design phase of the network. These calculations are usually very intensive and take a long time. Therefore they can not be performed in-time during the operation of the network.

Efficiency in a WiMedia network using DRP can be defined as the configuration with the minimal used MAS, which again implies the minimal usage of resources and maximum remaining bandwidth. In the following notation O_n stands for the number of *owned* MAS from node n. A node owns a MAS when it has reserved this MAS for transmissions or reception in the beacon period. R_n stands for the number of reserved beacon slots in the beacon period of node n. This can be own MAS, MAS owned by surrounding nodes or MAS marked as occupied from alien nodes. Furthermore the raised indices o and e indicate if the value is the *optimal* solution, or the *effectively* current allocation. Finally the second raised indices r or i show if the value must be an *integer* or a *real*. The integer notation represents the number of owned or reserved MAS. The real notation indicates how much of that MAS will actually be used according to the data rate requirements. Two examples will demonstrate the notation: $O_n^{o,i}$ are the owned MAS slots by node n for the optimal solution and integer counting, $R_n^{e,r}$ are the effectively used MAS of node n in real counting.

The effectiveness of the nodes is defined in two different ways. For the end devices the effectiveness is:

$$E_n^{ED} = \begin{cases} \frac{O_n^{o,r}}{O_n^{e,r}} \\ 0, \textit{ if data rate or delay requirements fail} \end{cases} \tag{1}$$

An effectiveness of 1 is the optimal solution; for sub-optimal solutions the numerator increases and the effectiveness closes zero. The notation in real values is used, to get a difference in the equations for increased transmit data rates, but still only using one MAS. For instance a node with low bandwidth requirements must always reserve at least one MAS. This can mean that even for the lowest possible and highest possible data rate still only one MAS is required. To reward nodes switching to a higher transmit data rate and thereby less occupy the channel, a real notation for the number of owned MAS is used. A higher data rate E_n^{ED} will change the efficiency of that end device to the positive.

For APs the effectiveness uses the sum of the number of used MAS (integer counting). An AP has to maintain reservations to the end devices, which can only be done in complete MAS slots. Consider a node with low bandwidth requirements, but strict timing delays. Optimally it could operate with two MAS slots. But due to already existing reservations no combination of two MAS might be available to satisfy the timing requirements. Hence a combination of three MAS must be used. If using the real counting of MAS, as for the end devices, no difference of the AP effectiveness would be measurable; the summed effectively used MAS portion would stay the same. But with the integer counting the extra MAS is measurable. The effectiveness of an AP is defined as:

$$E_n^{AP} = \begin{cases} \frac{R_n^{o,d}}{R_n^{e,d}} \\ \frac{R_n^{o,d}}{AR_n^{e,d}}, \textit{ if 90-100\% of the available MAS required} \\ 0, \textit{ if more than 100\% of the available MAS required} \end{cases} \tag{2}$$

The parameter A in the numerator for the case of 90-100% MAS utilisation must be greater 1. It artificially degrades the efficiency and prevents an AP of being overloaded and shifts AP assignments from end devices to surrounding APs if possible.

The utility function of each node is the sum of the efficiency of all nodes (end devices and APs) within range. Each node tries to maximize the utility function. For an end device the utility function is:

$$U_n = E_n^{ED} + \sum_{o \in D} E_o^{ED} + \sum_{p \in A} E_p^{AP} \tag{3}$$

For an AP the utility function is:

$$U_n = E_n^{AP} + \sum_{o \in D} E_o^{ED} + \sum_{p \in P} E_p^{AP} \tag{4}$$

D is the set of end devices on the same channel that are in range of node n. In analogue P is the set of APs on the same channel in range of node n.

Each node (AP and end device) has an algorithm implemented to calculate the MAS reservations, depending on the selected channels. This algorithm takes the APs as subject nodes and iterates the end device nodes in range and on the same channel. The end device with the earliest delay requirement will be served first and gets assigned the closest MAS to or below the delay. This is repeated, until all nodes have enough MAS to satisfy the delay, afterwards random MAS are assigned, to match possible data rate requirements. Each node must have at least one MAS per superframe.

To provide the required information of the surrounding nodes, the QoS requirements, neighbourhood relation and currently superframe structure is exchanged on a two-hop distance.

Each end device can choose which AP in range it selects. The decision uses the utilisation function. An end device compares the existing utilisation value and the to be obtained value when changing the AP by calculating the MAS reservations and utilisation value of the new setup. An access point change is only done, when an utilisation gain exists.

Analogous the APs also recalculate the MAS reservation and utility value, with changing channel selection.

Finally the processes for the end devices and APs of the distributed resource management algorithm based on game theory are as followed:

End device
1. Scan all channels for APs
2. Calculate MAS reservations and U_n for channels with APs in range
3. Select the channel with the best U_n
4. Periodically rescan other channels

Access point
1. Select channel (no AP or AP with worst RSSI)
2. Try to increase U_n by investigating possible channel change
3. Select channel with best U_n
4. Periodically recalculate

Mobile nodes are also supported. Therefore the optimal solution is calculated without them. Later, the mobile nodes are included in the system as a regular end device. They will leads to a constantly higher utilisation value, but still the algorithm finds the same fair solution.

5 Conclusions

In this work a resource management algorithm based on game theory for high data rate UWB networks was presented. The network consists of service access points, which provide access for wireless end devices to a wired network, such as LAN or Internet. The algorithm achieves a fair distribution of resources and adapts to changes in the radio channel or topology. Network efficiency is based on the number of used MAS slots, which also encompass bandwidth and timing requirements. The MAS reservation algorithm is essential for scenarios with high MAS utilisation, as the efficiency of the overall algorithm is tightly coupled to the efficiency of the MAS reservation for large loads.

The distributed approach does not require a dedicated node to compute the network parameters. Hence whatever parts of the network are failing, the network still tries to connect as many nodes to the APs as possible. The algorithm can be used in various applications: on-board networks, office and home WLAN or ad-hoc communication.

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