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ROPAS: Cross-Layer Cognitive Architecture for Mobile UWB Networks

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Abstract The allocation of bandwidth to unlicensed users, without significantly increasing the interference on the existing licensed users, is a challenge for Ultra Wideband (UWB) networks. Our research work presents a novel Rake Optimization and Power Aware Scheduling (ROPAS) architecture for UWB networks. Since UWB communication is rich in multipath effects, a Rake receiver is used for path diversity. Our idea of developing an optimized Rake receiver in our ROPAS architecture stems from the intention of reducing the computation complexity in terms of the number of multiplications and additions needed for the weight derivation attached to each finger of the Rake receiver. Our proposed work uses the Cognitive Radio (CR) for dynamic channel allocation among the requesting users while limiting the average power transmitted in each sub-band. In our proposed novel ROPAS architecture, dynamic channel allocation is achieved by a CR-based cross-layer design between the PHY and Medium Access Control (MAC) layers. Additionally, the maximum number of parallel transmissions within a frame interval is formulated as an optimization problem. This optimal decision is based on the distance parameter between a transmitter-receiver pair, bit error rate and frequency of request by a particular application. Moreover, the optimization problem improvises a differentiation technique among the requesting applications by incorporating priority levels among user applications. This provides fairness and higher throughput among services with varying power constraint and data rates required for a UWB network.

Keywords cognitive radio, joint power and frequency allocation, power aware scheduling, primary and secondary users, ultra wideband

1 Introduction

Ultra Wideband (UWB)[1] techniques are used extensively for higher data rates over short transmission ranges, especially for multimedia traffic. UWB spans over a 7.5GHz (3.1∼10.6GHz) bandwidth at a power level near the noise floor. However, the UWB transmissions can increase the noise floor and introduce interference on adjacent channels. This may result in substantial performance degradation to the existing users. To avoid such undesirable situations, Federal Communications Commission (FCC) defined the spectral mask of −41.3dBm/MHz for the UWB transmissions in certain overlapping bands. For example, the radar and satellite systems span over a bandwidth of 1.6GHz (3.1∼4.7GHz). Therefore, power control mechanisms and reduction of channel interference are important design issues in a UWB receiver.

Given limited radio spectrum available to accommodate an increasing number of users, the underlying system must adapt to the exponentially growing demand of spectrum access. Static channel allocation of licensed bands to SUs results in wastage of channel bandwidth, and in turn, lowers spectrum utilization. The spectrum utilization can be significantly improved with dynamic channel sensing and allocation of licensed bands, performed by a specially-designed radio technology called Cognitive Radio (CR)[2]. CR is a revolutionary technology that substantially improves spectrum efficiency with the aid of advanced spectrum sensing and dynamic channel assignment in licensed bands, but without actually obtaining a license. CR is primarily a software-defined radio that is aware of its surrounding environment[3], and is capable of sensing spectrum used by neighboring devices, changing frequencies, adjusting output power, or even altering parameters and characteristics of its transmission.

On the other hand, UWB communications are rich in multipath effects. In this paper, we make a novel effort in utilizing Rake filtering in our proposed Rake Optimization and Power Aware Scheduling (ROPAS) architecture to exploit effects of the multipath channels.

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In our ROPAS design, the unique multi-objective Rake optimization ensures minimal bit error rate (BER) for the receiving applications while strategically selecting an optimal number of multipaths among the many possible propagation paths. The joint optimization helps in reducing the computation complexity at the Rake receiver while minimizing interference for better estimation of transmitted bits.

The design of the medium access control (MAC) layer for the UWB network is significantly different from the traditional multihop ad hoc networks. The reason for this difference in design is due to the transmission power restrictions imposed on such UWB signals in the licensed bands by the FCC. The MAC layer protocol design should possess the salient features: (i) minimizing power consumption due to communications to reduce interference on the licensed users, and (ii) fair and efficient sharing of resources between communicating devices.

Now, power aware MAC layer with minimum interference can be efficiently developed when information can be exchanged with the PHY layer before allocating links to data traffic. This exactly is the central idea of our novel ROPAS architecture. In this paper, we take advantage of cross-layer design between the PHY and MAC layers for CR-aided dynamic channel assignment in the UWB network. However, the CR-based dynamic channel assignment cannot be achieved in a straightforward manner, and involves inter-related issues such as "free" (i.e., idle) channel detection, interference measurement, multipath selection, and power control. For example, the interference and the channel fading characteristics have to be considered from the PHY layer so that the data frames can be transmitted with less interference. Furthermore, transmission power control over the links is performed by the MAC layer with an objective of limiting power while satisfying the packet transmission requirement (e.g., delay, distance). Thus, the cross-layer sharing of information between these two layers is indispensable, especially for CR-based mobile nodes in a dynamic network, since the channel conditions vary randomly with varying mobility patterns. At the same time, in ROPAS, the cross-layer-based power control and link scheduling strategy help the CR to impose a limit on the transmit power in each frame interval. The CR uses increased transmission power for delay sensitive traffic to reach the destination in minimum number of hops and therefore, minimum delays while it employs reduced transmission power for delay tolerant services.

In our cross-layer design and simulation, we have chosen the UWB (3.1∼10.6GHz) for link allocation and for traffic communication purposes due to its high data rate on each sub-channel of 528MHz bandwidth[1]. The main contributions of this paper are as follows.

- We present a multi-objective optimization problem for the Rake receiver to reduce computational complexity.
- We present the cross-layer multi-objective optimization design for dynamic frequency selection with optimal transmission powers allocated to each subframe, an optimal partition of a licensed sub-band.
- We discuss the cross-layer design of the CR-based priority based on scheduling while supporting the maximum number of parallel transmissions within a frame interval.

The rest of this paper is organized as follows. Section 2 deals with the previous work on dynamic channel allocation strategies. Our proposed algorithm, ROPAS is described in Section 3. Section 4 illustrates the optimal power allocation strategy based on distance and priority differentiations. Simulation results are discussed in Section 5 followed by the conclusion in Section 6.

2 Related Work

Dynamic channel allocation in mobile networks has been addressed by previous work in myriad ways. The distributed, fault-tolerant allocation[4] depends much on the channel usage information of the interfering neighbors of a requesting user, based on which it can compute the best channel allocation. This strategy involves a high message complexity due to the exchange of channel usage information of all its one-hop neighbors. The other research on dynamic channel allocation[5] is based on a mutual exclusion between the "request" and "reject" messages for allocating a group of channels. But, this strategy suffers from the problem of fairness among requesting users with additional problem of message complexity due to the exchange of "request" and "reject" messages. An improved version of the channel allocation is discussed in [6] where channel allocation is based on the ratio of the serviced data rate to the required data rate. Additionally, the power distribution algorithm in this research work "adjusts" the average transmit power of the channel based on the received signal-to-noise ratio per user. But this allocation strategy may give rise to a serious problem: assume that a channel is allocated to a loss-sensitive application and the channel suffers from deep fading while their power distribution strategy decides to decrease ("adjust") the average transmit power on this channel. This will result in loss of the entire transmission due to poor channel conditions and cause a dramatic performance degradation. Our proposed ROPAS cross-layer architecture has a solution to this problem. Scheduled links are allocated power by the CR based on the retrieved information about channel conditions from the physical layer.

The design of efficient MAC layer protocol with low power consumption and strict computational complexity is a persisting research challenge. The authors in [7] have dealt with these issues using the margin-based power allocation scheme to maintain power constraint along with an exclusive region based scheduling algorithm to reduce interference. But this research work suffers from the inherent problem of centralized decisions taken by a centralized controller for power allocation and slot allocation. Therefore, the system becomes much more complex with the increase in number of UWB devices, resulting in heavy overhead due to sharing of varying users with the centralized controller. The location based MAC layer protocol and routing[8] depends on the distance information to achieve low power levels, increased lifetime and improved network performance. Saving power in each UWB device is achieved by using a sleeping interval when the devices are not participating in active transmissions. Again this paper works on the trade-off between power constraints and network latency when our main focus is on power constrained protocol design. The application of CR[9] deals with the network layer perspective in UWB networks. The routing decisions are made on the basis of a cognitive cost function that takes care of important issues like synchronization, end-to-end delay and coexistence with licensed users. Our proposed architecture deals with a cross-layer MAC optimization protocol where the CR in each UWB device decides upon allocating channels to its applications within the imposed power constraints. Additionally, proportional fairness is achieved by the unique priority scheduling performed by the CR.

3 ROPAS Architecture

The central idea of cross-layer design is to improve the overall performance of wireless networks with the exchange of information between the different layers of the protocol stack. This was not possible in traditional wireless networks. Recent research on cross-layer design[10,11] showed a substantial improvement in the routing efficiency, throughput, fairness and delay variance among different applications. Physical layer information exchange[12] with the MAC and network layer has also exhibited superior network performance. We made an effort in utilizing multi-objective optimization techniques in the CR-based cross-layer design which involves the MAC and PHY layers.

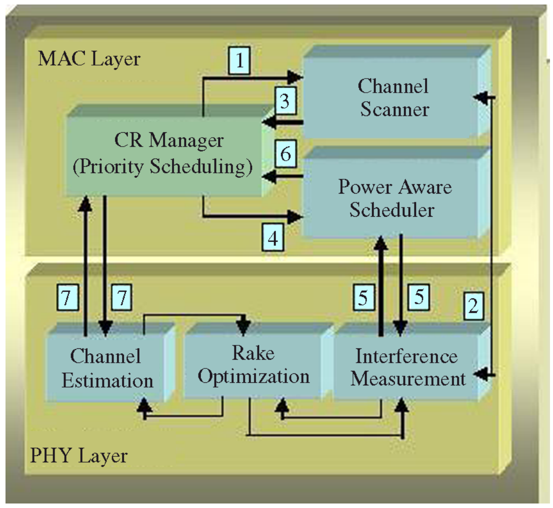

Fig.1. Cross-layer design of the ROPAS architecture.

The ROPAS architecture is shown in Fig.1 and the entire protocol is described in several steps (i.e., marked by numbers). In the proposed ROPAS, in addition to traditional CR modules in the PHY and MAC layers, several functional modules are included in order to improve the collaboration between the PHY and MAC functionalities as shown in Fig.1. All the central decisions are taken by the CR Manager (CRM) which also has the capability of interaction between different modules. The other two modules in the MAC layer are responsible for efficient dynamic channel allocation among mobile nodes with limiting power constraints. The Channel Scanner (CS) divides the entire UWB into smaller sub-bands and scans these sub-bands in periodic intervals for possible "free" (not used by licensed users) channels. The next module is called the Power-Aware Scheduler (PAS) which aims at a multi-objective joint power control and link scheduling of data frames. Additionally, it also performs the hybrid queuing strategy to achieve fairness among requesting applications. The three modules at the bottom of Fig.1 are associated with the PHY layer of each node in the network. One of the modules is the Interference Measurement (IM) which measures the interfering power sensed in each sub-band due to users in adjacent sub-bands. The PAS works with the IM to limit transmission power in any particular sub-band within the permissible limits (−41.3dBm/MHz[1] or 0.039mW/528MHz for UWB communications). The Rake Optimization Module (ROM) deals with the PHY layer Rake receiver. This multi-objective optimization computes a minimal number of Rakes or fingers needed by the Rake receiver for maximum signal power and hence maximum signal-to-noise ratio (SNR) at minimal BER. The Channel Estimation Block (CEB) estimates the fading condition of the channel as well as the channel error rates. The CEB shares the cross-layer information with the CRM to select the best link (in terms of fading and error rate) for data transmission among the adjacent one hop neighbors.

Our proposed architecture addresses these two issues: the dynamic channel allocation for the transmitting applications and the Rake optimization for receiving processes. The Rake optimization is a purely PHY layer issue and utilizes the interference power information from the IM to optimize the number of propagation paths selected for minimal BER. For dynamic channel allocation, let us consider an example to get a better understanding of our cross-layer design of ROPAS. Seven steps are involved in the entire channel allocation process.

Step 1. An application arrives at the CRM with its link request and delay constraint. The CRM refers to the CS for possible "free" channels.

Step 2. The CS, with ready reference to the IM module for probable interference power, detects the "free" channels. It is noted that the IM module is located in the PHY layer.

Step 3. Upon the response from the IM, the CS sends the detected free channels with their respective identifications to the CRM. Therefore, the CRM has now the complete information about the free channels for the requesting applications.

Step 4. The CRM requests the PAS module for transmit power limits on each of these "free" channels. The CRM also sends information about the delay constraints for the requesting application.

Step 5. The PAS refers to the IM for signal-to-interference and noise ratio needed for joint power control and link scheduling; the PAS module divides the MAC layer frames into subframes (based on delay constraints of the requesting applications) and assigns a group of links to each subframe. The module also allocates a group of transmit powers based on the delay constraints.

Step 6. The PAS sends the information to the CRM about the frame interval, fraction of each subframe and probable groups of transmit power allocation to each subframe.

Step 7. Finally, the CRM checks with the CEB on probable error rates and fading conditions based on the information received from the PAS module. Then, the CRM allocates the power constrained links to the frames determined by the PAS.

It can be seen from these steps that for a power constrained link an appropriate collaboration between different modules enables the data transmission in an optimal manner in terms of current channel and link status (i.e., delay constraint of the requesting user, utilization of the channel with power constraints, and the interference of link). The collaboration considers two critical issues in the subframe transmission: the channel characteristics for dynamic channel allocation and the transmission power for reducing the interference. In the following subsections, we will describe each module in detail and illustrate the interactions in each module.

3.1 Rake Optimization Module

In this subsection, we discuss the Rake optimization, which is an enhanced Rake receiver module in the PHY layer shown in Fig.1. The Rake optimization employs a multi-objective optimization strategy for an optimal selection of multipaths out of the several possible propagation paths.

A Rake receiver is generally used for UWB networks. Since UWB communications are rich in multipath effects, Rake receivers are used for accumulating the energy in significant multipath components. It consists of a bank of correlators or fingers where each finger is synchronized to a multipath component. The output of each finger is coherently combined by using different techniques like Maximal Ratio Combining (MRC)[13], Minimum Mean Square Error, etc.

The complexity in computing the Rake receiver output involves two parts: (i) multiplications of $\{N \times M\}$ matrix with $\{M \times N\}$ matrix give $O(MN^2)$[13] and (ii) additions of the above two matrices of similar dimensions result in a complexity of $O((M-1)N^2)$, where M and N denote the number of correlators and the weights assigned to each correlator, respectively. Our idea of developing an optimized Rake receiver stems from the intention of reducing the computation complexity in terms of the number of multiplications and additions needed for the weight derivation attached to each finger of the Rake receiver. We have chosen MRC Rake receiver for its lower computation complexity when compared to other Rake receivers.

To illustrate our assertion, we assume that the i-th received signal at time instant t is $r_i(t)$. The output of the Rake receiver $y_i(t)$ for the i-th received signal with R fingers or correlators can be given by:

$$y_i(t) = \gamma^{\mathrm{T}} \times \sum_{j=0}^{R-1} r_i(t - \delta_j), \tag{1}$$

where $\gamma = [\gamma_0, \ldots, \gamma_{R-1}]^{\mathrm{T}}$ are the weights associated with each finger of the Rake receiver, T is the transpose operation and δ_j is the delay associated with j-th correlator of the Rake receiver to capture the multipath signal from its predefined delayed path. Now, the computation complexity depends on the number of fingers used and their corresponding finger weights. In order to reduce the computation complexity, we can strategically select an optimal number of fingers out of many multipaths in UWB communications. If the value of M and N can be reduced, then the computation complexity can be reduced to a great extent. Hence, the basic idea of our optimal selection of a few fingers will reduce M and the corresponding reduction in weights will reduce N.

Let $\mathcal{K} = \{1, 2, \ldots, k, \ldots, K\}$ be the set of all the multipaths. The energy-to-noise ratio (ENR_k) in k-th multipath can be written as[1]:

$$ENR_k = \frac{P_k \times \tau_c}{N_0 \times W \times \sigma_T}, \tag{2}$$

where P_k is the average power received in the k-th multipath, τ_c is the coherence bandwidth of the UWB channel, N_0 is the one-sided power spectral density of the background Additive White Gaussian Noise (AWGN), W is the signal bandwidth and σ_T is the standard deviation of the AWGN noise within the symbol duration, T.

The Rake optimization is to strategically select only a few of the multipaths out of all the possible ones. The reason behind this is two-fold: (i) received signal energy from each and every multipath may not improve the total desired signal energy at the Rake receiver, and (ii) delayed multipaths may suffer from severe fading or may have been corrupted due to channel interference, thereby resulting in increased BER. The idea is to optimize the number of multipaths chosen so as to maximize the ENR_k for the k-th path. On the other hand, the optimization needs to minimize the overall system *BER*, which implies minimization of the overall bit energy, E_b. Therefore, it becomes a multi-objective optimization.

The multi-objective function in multipath k with power P_i^k for the i-th UWB receiver in the presence of interfering U nodes can be represented finally as below:

$$\max\left(\frac{P_i^k}{\sum_{j=0, j\neq i}^{U-1} P_j^k}\right), \quad k \in \mathcal{K}. \tag{3}$$

Then maximizing (3) for all $k \in \mathcal{K}$.

$$\begin{aligned}\min\left(\frac{E_b}{N_0}\right) &= \min\left(\sum_{k=0}^{K-1} P_i^k + \sum_{j=0, j\neq i}^{U-1}\sum_{k=0}^{K-1} P_j^k\right) \\ &= \min\left(\sum_{k=0}^{K-1} P^k\right) \quad \text{over all the users.}\end{aligned} \tag{4}$$

Next, let $\phi = \{1, 2, \ldots, k', \ldots, K'\}$ be a selection from $\mathcal{K}$ i.e., $\phi \subset \mathcal{K}$. Hence, our goal is to choose a subset ϕ that maximizes the power given in the first objective while maintaining a low BER. Therefore, K' is the optimized number of paths in the set of paths ϕ, and $\mathcal{K}$ is the number of multipaths in the set of possible propagation paths. Therefore, the optimization problem with two maximizing functions $f_0(k)$ and $f_1(k')$ can be rewritten as:

$$\begin{aligned}\max f_0(k) &= \frac{P_i^k}{\sum_{j=0, j\neq i}^{U-1} P_j^k}, \quad k = 0, \ldots, \mathcal{K}-1, \\ \max f_1(k') &= \sum_{l=0}^{K'-1} P^l.\end{aligned} \tag{5}$$

To solve this multi-objective functions, we can either create Pareto-optimal charts[14] and select the best solution from the same or combine them as done here. In fact, another approach is to select a set of real values λ_i which refers to the multiplier for the i-th maximizing objective function, $f_0(i)$. Hence, our new objective function $L(\phi)$ becomes:

$$L(\phi) = f_1(k') - \sum_{i=0}^{K'-1} \lambda_i \times f_0(i). \tag{6}$$

This is still a combinatorial optimization problem. To reduce it to a linear Integer Programming (IP) problem[14], we introduce a set of variables X_i defined as:

$$X_i = \begin{cases} 1, & \text{if multipath is selected and,} \\ 0, & \text{if multipath is not selected.}\end{cases}$$

Therefore, the problem in (6) can be reformulated over the set X (constituting individual $X_i's$) as:

$$\begin{aligned}L(X) &= X \times f_1(k') - \sum_{i=0}^{K'-1} \lambda_i \times f_0(i) \\ &= \sum_{i=0}^{K'-1}\left[X_i \times P^l - \lambda_i \frac{X_i \times P_j^i}{\sum_{l\neq j} P_l^i}\right], \\ &\text{subject to } X_i \in [0, 1].\end{aligned} \tag{7}$$

It is easy to see that this is a linear IP problem and can be easily solved by using a standard solver like the

Branch-and-Bound method. We have used GLPK[15] (version 4.10) for solving this multi-objective optimization problem.

```
Declare parameter m as an integer > 0
  Declare parameter n as an integer > 0
    Declare Power[i][j] >= 0
    Declare λ[i] >= 0
        Range of I from 1 to m
        Range of J from 1 to n
        Variable X[i] is binary // for Integer Programming
            x[i] = 1 means the path is selected by the CR
            x[i] = 0 means the path is rejected by the CR
        such that Power [i][1] <= 0.039
            minimize path for (∑_i X_i * ∑_j Power [i][j])
              − ∑_i(λ[i] * X[i] * Power[i][1])
              /(∑_j Power[i][j] − Power[i][1]);
```

Fig.2. Pseudo code for the Rake multi-objective optimization.

Our implementation of the IP and the pseudo-code is shown in Fig.2. First, we declare a variable, $Power[i][j]$ which represents the power received by the Rake receiver from the i-th multipath carrying information of the j-th user. $Power[i][1]$ is the power received by the desired UWB Rake receiver ($j = 1$) from the i-th multipath. This implies that $Power[i][j]$ with $j \neq 1$ is the received interference power from the i-th multipath. We have also declared the multiplier, λ_i (i.e., $\lambda[i]$ in Fig.2) and the binary variable, X_i (i.e., $x[i]$ in Fig.2) for our joint optimization. The transmission power constraint on each multipath for UWB communication is limited to 0.039mW. Therefore, for any correlator, we impose a power constraint of 0.039mW as any multipath with higher power values may be corrupted due to interference. With this underlying logic for our optimization problem, we solve (7) for the optimal selection of paths as shown in Fig.2.

3.2 Interference Measurement

The IM is another module in the PHY layer involved in Steps 2 and 5 as shown in Fig.1. This module is needed to calculate the signal-to-interference noise ratio (SINR) which estimates the ratio of power due to the allocated link to power due to other adjacent interfering links at a soft-decision variable. Let us assume that M information bearing symbols, $S_k(1), \ldots, S_k(M)$, independently and identically distributed (i.i.d) are chosen from a finite set with zero mean. The mean $E[S_k(m)]$ and variance, $E[|S_k(m)|^2]$ for the k-th link are defined as:

$$\begin{cases} E[S_k(m)] = 0, \quad \text{and} \\ E[|S_k(m)|^2] = P_k, \quad 1 \leqslant m \leqslant M, \quad 1 \leqslant k \leqslant L, \end{cases} \tag{8}$$

where P_k represents the signal power on the k-th link.

Then, the expected value of SINR at the k-th link among L links is given by:

$$\begin{aligned} SINR_k(P) &= \frac{G_k \times P_k}{\sum_{l=1}^{L} P_l \times G_{k,l} + \sigma_k^2}, \\ &= \frac{P_k}{\sum_{l=1}^{L} P_l \times \left(\frac{G_{k,l}}{G_k}\right) + \frac{\sigma_k^2}{G_k}}, \quad 1 \leqslant k \leqslant L, \end{aligned} \tag{9}$$

where $P_k \geqslant 0$ is the transmitted power on link k. We further define the transmit power vector, $\boldsymbol{P}$ as

$$\boldsymbol{P} = (P_1, \ldots, P_L) \in \Re_+^L, \tag{10}$$

where $\boldsymbol{P}$ is also referred to as the power allocation vector. The first term in the denominator of (9) gives us the interference power in the k-th sub-band prior to link's data transmission. This interference is called the *interference temperature* caused by concurrent communications in the adjacent channels. This value is exchanged with the PAS module for link allocation. $G_k \geqslant 0$ is the path gain on the allocated link k and depends on the channel allocation and the state of the wireless channel. $G_{k,l} \geqslant 0$, $l \neq k$ is the path gain between the link l and link k. Therefore, if the transmit power on link l is P_l , then the expected interference on link $k \neq l$ is $P_l G_{k,l}$. Additionally, if $G_{k,l} = 0$, then the link k is said to be orthogonal to link l. Again, $G_{k,k} \geqslant 0$ represents the self and inter-symbol interference which occurs due to the time dispersive nature of the wireless channel. $\sigma_k^2 > 0$ is the Gaussian noise variance at the output of link, k.

3.3 Channel Estimation Block (CEB)

The CEB module is involved in Step 7 of our cross-layer dynamic channel allocation strategy. The minimum mean square estimation (MMSE)[16] algorithm runs at the CEB to determine existing channel conditions between the network nodes within their communicating ranges. The CEB also gets an estimate of the error rate due to existing channel conditions. These estimates are calculated in short durations to take care of changing topology/routes caused by mobility of the nodes. The CRM refers to these estimates for the requesting service and assigns the link out of a possible multiple set of selected links chosen by the PAS module. For example, the CRM would decide to assign links with channel error rate 10^{-3} (rapid fading characteristics) to frames of a speech telephony application and will assign a link with channel error rate 10^{-5} (slow fading characteristics) to frames of a video telephony application.

3.4 Channel Scanner

The Channel Scanner is involved in Steps 1, 2, and 3 of our channel allocation strategy shown in Fig.1. The CR divides the UWB into narrow sub-bands or channels of bandwidth 528MHz[1]. CR scans each of these sub-bands and detects them as "free channels" based on the "interference temperature" obtained from (9). These "free channels" can be assigned for its own data transmission or for forwarding traffic of its one hop neighbors. The CR detects the "free" channels with the help of the IM and stores them in a "free channel pool" as shown in Fig.3.

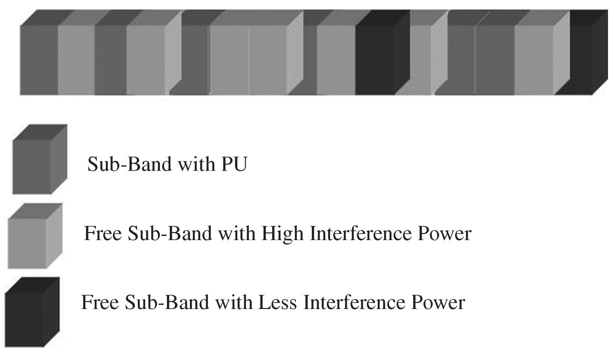

Fig.3. Channel assignment based on the "free" channels detected by the IM in the UWB (3.1~10.6GHz).

3.5 Power Aware Scheduling

The CR divides a MAC layer frame into smaller synchronized subframe intervals, assigns a set of links to each subframe, and allocates transmitting power to each of the set of links. This process is done by the PAS module, which is involved in Steps 4, 5, and 6 as shown in Fig.1. Let us assume a finite frame interval F and each subframe interval to be SF, a perfect multiple n of F. Thus, we have a set of subframe intervals $\chi = \{1, 2, \ldots, n\}$. Again, the PAS module divides the entire sub-band of N links of 528MHz into smaller subsets M of bands or links of bandwidth $(528/n)$ such that $M \times n = N$ as illustrated in Fig.4.

We consider that any one of these subsets, M can be allocated to each subframe based on the power constraint. We also assume that $A = \{SF_i\colon\ i \in \chi\}$ be a system of subsets of F with

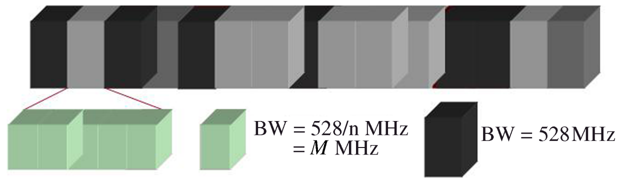

Fig.4. Sub-band division into multiple frames in Power Aware Scheduling illustrated in UWB.

$$\bigcup_{i\in\chi} SF_i = F \quad \text{and} \quad \forall_{i\in\chi} SF_i \bigcap SF_j = 0, \quad i \neq j. \tag{11}$$

(11) indicates that a frame is divided into disjoint subframes within the frame interval. One additional point to note is that F can also represent a frame and correspondingly, SF is a subframe of F. Let ξ represents the real function that denotes the fraction of frame occupied by the subframe, $\xi : A \to [0, 1]$ such that

$$\begin{cases} \forall_{i\in\chi}\xi(SF_i) \geqslant 0, \quad \xi(0) = 0, \quad \text{and} \\ \xi\Big(\bigcup_{i\in\chi} SF_i\Big) = \sum_{i\in\chi} \xi(SF_i) = \xi(F) = 1. \end{cases} \tag{12}$$

Here $\xi(SF_i)$ denotes the i-th fraction of the frame with interval SF. We have also related $\xi(SF_i)$ with the frequency of allocation of the power vector $\boldsymbol{P}(SF_i)$ to the links allocated to the i-th subframe. $\xi(SF_i) = 0$ implies that the power vector $\boldsymbol{P}(SF_i)$ is not utilized by the links for that subframe.

Now for each link within a set M, $l \in M$, we associate a set function $P_l : A \to \Re_+$ (a positive real space). Let us define a power vector $\boldsymbol{P}$ as the set of possible transmit powers which satisfy $\boldsymbol{P} = (P_1, \ldots, P_l) : A \to \Re_+^L$. If we define $\phi(SINR_k(P(SF_i)))$ as the average data rate for link k in the subframe with $SINR_k(\boldsymbol{P}(SF_i))$ defined as in (9), then the expected data rate $\tau_k(\boldsymbol{P}, \xi)$ can be written as[17]:

$$\tau_k(p, \xi) = \sum_{i\in\xi} \xi(SF_i)\phi(SINR_k(\boldsymbol{P}(SF_i))). \tag{13}$$

Now, with the above expected data rate and SINR, we define the joint power control and link scheduling strategy as: with given values of A and F, ξ decides the length of each subframe and based upon the subframe interval, assigns a group of links to each subframe. This is similar to frequency division multiplexing, where the entire bandwidth is divided into frequency slots. Therefore, link scheduling can be modeled as a function of ξ. Now power scheduling relates to allocating transmit power to the links in each subframe. Therefore, the joint power control and link scheduling can be mathematically defined as:

- choosing $\xi : A \rightarrow [0,1]$ while satisfying (12), and
- determining $\boldsymbol{P} : A \rightarrow \Re_{+}^{L}$.

The CR computes the joint power control and link scheduling in two different ways for two different traffic patterns as follows.

Delay Sensitive Traffic: for delay sensitive packets (e.g., delay less than 100ms), higher power vector needs to be assigned to each subframe which results in higher transmit power within each frame interval. Therefore, the joint strategy tries to minimize the value of ξ fraction of each subframe and maximize the power vector in each subframe. In other words, it maximizes the transmit power in each link. The joint optimization can be expressed as:

$$\min \xi,$$
$$\max \sum_{k=1}^{M} P_k, \quad k = 1, 2, \ldots, M.$$

such that

$$\sum_{i \in \chi} \boldsymbol{P}(SF_i)\xi(SF_i) + \sum_{i=1}^{n}\sum_{k=1}^{M}\sum_{l=1}^{L} \xi(SF_i) P_l G_{k,l} \leqslant 0.039. \tag{14}$$

Delay Tolerant Traffic: similarly, the strategy for delay tolerant packets (e.g., delay greater than 100ms) is to maximize the value of ξ while re-using the links with higher frequency). As we mentioned earlier, the value ξ has a direct correlation with the frequency of using a certain power vector. Since we use larger subframes, the transmit power has to be limited in each subframe in this case. This joint optimization can be written as:

$$\max \xi,$$
$$\min \sum_{k=1}^{M} P_k, \quad k = 1, 2, \ldots, M, \tag{15}$$

with constraint defined as in (14).

Here L is the total number of links in the entire UWB. This optimization is solved in a similar way as computed by a Rake Optimization. Choice of ξ also plays a vital role in power control. Higher value of ξ implies higher subframe duration (rather less number of subframes), and higher frequency of usage of power vector, $\boldsymbol{P}(SF_i)$ for links used in the i-th subframe (since $\xi(SF_i)$ relates to the frequency of allocation of power vector $\boldsymbol{P}(SF_i)$ in the i-th subframe). Thus, (14) will limit the transmit power dissipated over the frame duration. On the other hand, lower values of ξ implies lower frequencies of utilization of a certain power vector and encourages the use of higher transmit powers with the allocated links in each subframe. In addition, we can further define priority according to the requirement of given applications. To illustrate this point, the CR can use smaller values of ξ for real time traffic (i.e., delay sensitive) which encourage higher values of transmit power in each subframe. Thus, it increases the transmission range of each UWB node while reducing the number of hops to its destination, thus results in minimum transmission delay. Again, the non-real time applications (i.e., delay tolerant) can be assigned higher values of ξ to use lower transmit power in each subframe resulting in decreased transmission range.

4 Priority-Based Scheduling

In this subsection, we will formulate the optimization problem for joint power control and link scheduling for different application originating from one UWB node or from other competing nodes. We know that higher spectral efficiency can be achieved with increasing parallel transmissions in minimum number of time slots per frame. Thus, we will concentrate our attention in scheduling maximum number of parallel transmissions in minimum number of time slots which is defined a variable NP where $NP_{i,j}$ represents the i-th bit of the j-th user application. The other aspect of our constrained optimization would be to restrict the multi-access interference (MAI) within the FCC's permissible limits.

$$\max \ NP_{i,j}$$
$$\text{s.t. } \frac{P_{i,k}}{\sum\limits_{p=0,p\neq k}^{M-1} P_{i,p} \sum\limits_{l=0}^{N-1} c_p^l c_p^k + \sigma_k^2} \geqslant SNR_{\rm th}, \tag{16}$$

where σ_k^2 is the additive White Gaussian noise power, $SNR_{\rm th}$ is the minimum SNR for transmission power in a particular slot. If the SNR of a user is higher than the $SNR_{\rm th}$, the signal can be received successfully. Otherwise, the transmission fails. The signal power for the i-th bit for the k-th user is represented by $P_{i,k}$ and that for the p-th interfering users is represented by $P_{i,p}$. The l-th chip of the spreading sequences for the p-th and k-th users is denoted by c_p^l and c_p^k respectively. The cross-correlation of two different spreading sequences is not negligible. Hence, this term is added in the interference term of (16). The first term in the denominator of the expression for the constraint represents the MAI from $(M-1)$ users.

Now the signal power for an application is defined in our work as a function of channel conditions, priority level in the queue and the distance between the transmitting UWB node and the receiving node.

According to the FCC's restriction in transmission power, the maximum transmitting range can be 10m[1]. Again, near-far interference is a persisting issue in the case of Code Division Multiple Access (CDMA) systems. To reduce the near-far interference, the transmitter requires less power if the receiver is near to it and more power for a receiving node far away from it. We will represent the distance variable between the i-th transmitter and j-th receiver by $d_{i,j}$. So, if the distance between a transmitting node and a receiving node is less than $d_{i,j}$, the transmission power level is reduced by half of its current value. If greater than $d_{i,j}$, the existing power level is increased twice of its current transmission power level.

Next, we will consider the channel conditions. This gives rise to the cross-layer sharing of information between the MAC and PHY layers. In our research, we have considered the BER as the measure of the channel conditions. The BER value is evaluated by the CEB and shared with the BER. For BER values in the order of 10^{-3} or higher, the channel is considered to be poor and data from the low priority queue will be preferred. For BER less than this value, data from high priority queue are preferred or data are transmitted at higher power levels and can also support higher data rates.

Finally, we will consider the priority queue operated by the CR. This module is depicted in the CRM module of Fig.1. Priority is decided based on the data rate requested by an application or higher transmit power requests which in turn, demands for lower BER ($< 10^{-3}$). Now based on these demands, the CR maintains 2 queues, one with higher priority ($Pri = 2$) and the other with low priority ($Pri = 1$). The unique feature added to our priority queuing strategy is that of frequency of requests by the same application. If a same application, irrespective of its priority level, requests for channel assignment more than once, the signal power is reduced by the value of its corresponding frequency of request. This is done to achieve fairness among the requesting applications.

Now the signal power $P_{i,j}$ for the j-th user application in the i-th slot is proportional to the priority of an application, BER and the distance between the transmitter-receiver pair. Additionally, $P_{i,j}$ is inversely related to the frequency of request of an application. Therefore, the expression for the $P_{i,j}$ can be expressed as:

$$P_{i,j} = K\frac{\boldsymbol{P} \times 10_j^{\gamma} \times d_{j,k}}{f}, \tag{17}$$

where γ is the positive exponent of the BER, K is the proportionality constant, $d_{j,k}$ is the distance between the j-th transmitter and the k-th receiver. Here f represents the frequency of the requesting application.

The constraint in (16) can now be expressed as

$$\frac{K \times \boldsymbol{P} \times 10_j^{\gamma} \times d_{j,k}}{f \times IP_j} \geqslant SNR_{\rm th}, \tag{18}$$

which can be re-written for interference power IP_j as,

$$\frac{K \times \boldsymbol{P} \times 10_j^{\gamma} \times d_{j,k}}{f \times SNR_{\rm th}} \geqslant IP_j. \tag{19}$$

5 Simulation Results

In this part, we study the performance of our proposed optimal power allocation with scheduling performed by the CR. The simulation is performed using software models written in C++. This optimal priority based scheduling is simulated by using the GLPK[15] tool. The UWB is divided into 15 sub-channels, each of 528MHz bandwidth. The IM computes the SINR in each sub-channel and based on the joint power control and link scheduling policy, links are assigned to different slots within frame duration of 0.5ms. The proportional constant is considered to be 10^{-18}[7] and the SNR threshold is taken to be 10dB. The maximum transmission power is set to 10^{-13}W. The channel is assumed to have Gaussian noise power of 10^{-20}W. The performance of our proposed optimization architecture is evaluated from the following three aspects.

- Optimal number of correlators needed by a Rake receiver to improve the overall system BER.
- Power limits in different subframe intervals within a frame interval when joint power control and link scheduling are used in our ROPAS design.
- Optimal value of slot assignment and its variations with improvements in BER values.

5.1 Multi-Objective Rake Optimization

The simulation results in the PHY layer for multi-objective optimization for Rake receivers are discussed in the following three phases:

- selection of values, λ_i's,
- strategic selection of multipaths by CR-equipped optimal Rake receiver, and
- joint optimization achieved using the GLPK tool with the selected multipaths and as well as achieving desirable BER values.

Path 1 ($P1$)	Path 2 ($P2$)	Path 3 ($P3$)	Path 4 ($P4$)	Path 5 ($P5$)	Path 6 ($P6$)	Path 7 ($P7$)	Path 8 ($P8$)	Path 9 ($P9$)	Path 10 ($P10$)
0.0096	0.0509	0.0972	0.143	0.31	0.18	0.08	0.136	0.124	0.38

(a)

Path 2 ($P2$)	Path 3 ($P3$)	Path 4 ($P4$)	Path 5 ($P5$)	Path 6 ($P6$)	Path 7 ($P7$)	Path 8 ($P82$)	Path 9 ($P9$)
2.19×10^{-3}	1.79×10^{-3}	2.1×10^{-3}	1.26×10^{-2}	4.82×10^{-3}	4.4×10^{-3}	1.86×10^{-3}	6.41×10^{-3}

(b)

Fig.5. (a) Values of Lagrange multiplier's, $\lambda_i' s$ for all 10 paths. (b) Strategic selection of propagation paths based on BER values by our optimization algorithm when path 1 is already selected.

Selection of λ_i*'s*: the UWB signal experiences multipath fading. Depending upon the channel delay profile, the signal energy reaching the receiver via certain multipaths with considerable delay, but are still resolvable, can still be selected by the S-Rake. But a smaller value of λ may select path 1 but may exclude path 9 or 10 since it does not maximize the second term in (7). The values of $\lambda_i' s$ for different multipaths for its selection by the S-Rake are detailed in Fig.5(a).

Strategic Selection of Multipaths: the optimization algorithm selects path 1 with assigned value of λ_i. The BER achieved through our simulation is 2.34×10^{-3}. This result validates our optimization algorithm as we know that the first multipath component will always be the strongest path with most of the received signal power. Again with the selection of the Lagrange multipliers for all the 10 multipaths, all the 10 propagation paths are selected by our algorithm, but the BER achieved is 3.82×10^{-2}. The degradation in BER is due to the addition of all the remaining 9 paths with the strongest first multipath. This result validates the fact that all the multipaths do not carry adequate signal power, but also MAI power introduced in multiple access based UWB networks. The predominance of the MAI power in certain paths leads to such increased BER. These results help us to check the correctness of our optimization algorithm by varying the values of the Lagrange multipliers $\lambda_i' s$ of Fig.5(a). When path 10 is chosen along with path 1, BER is 1.6×10^{-2}.

Now, if we carefully look at Fig.5(b), we will see that paths 2, 3, 4 and 8 can be chosen along with path 1 for a better BER performance.

Let us see how it can be achieved by varying values of the Lagrange multipliers $\lambda_i' s$. The strategic selection of the selective multipaths by the S-Rake is demonstrated in Fig.6. Therefore the optimization algorithm computes a combination of paths 1, 3, 4, and 8 as the final optimal path selection which maximizes the desired signal power over the MAI power and as well as minimizes the BER. This observation is supported by our simulation results shown in Fig.7 obtained with the GLPK tool with increasing iterations of path selection.

Joint Optimization for Acceptable BER: initial value of path 1 is stored in a database that results in a BER of 2.34×10^{-3}. We have chosen the reference BER of 2.54×10^{-3}, a stringent value closer to the BER of the strongest path, path 1 to obtain better results. Therefore, the optimization algorithm now runs with the dual constraints of $BER < 2.54 \times 10^{-3}$ as well as $X_i \in [0, 1]$. Fig.6 explains the lists of path selections and the optimized path selection. Fig.7 shows the next strategic selection is path 3 with BER of 1.79×10^{-3} (refer to Fig.5(b)). Now it can choose either path 2 or 4 to satisfy the constraint of BER. Finally, it chose path 4 in third iteration with BER of 1.9×10^{-3}. The final selection with BER constraint is path 8 with BER of 1.75×10^{-3}, supporting the assertion that the addition of selective paths results in minimal BER. Additional iterations lead to the paths that do not satisfy the constraint, thereby terminating the optimization algorithm after the fifth iteration.

Selection of Paths (P)	Bit-Error Rate
$P1$, $P2$, $P3$, $P8$	2.29×10^{-3}
$P1$, $P3$, $P8$	1.9×10^{-3}
$P1$, $P3$, $P4$, $P8$	1.75×10^{-3}

Fig.6. Strategic selection of paths for optimal BER.

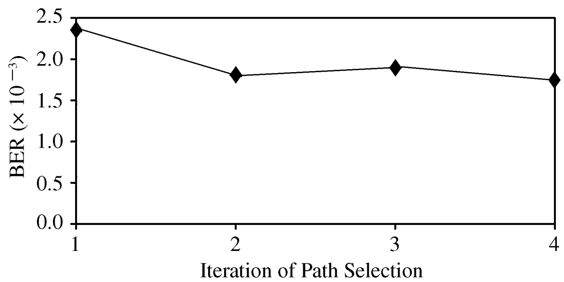

Fig.7. Reduction of BER with increase in iteration of path selection.

5.2 Power Aware Scheduling in ROPAS

The simulation for the joint power control and link scheduling provides informative results concerned with the varying applications with varying delay constraints. Fig.8 describes the scenario for four subframe intervals in one frame interval with $\xi = 0.5$. The unit value of ξ also implies that the lower frequency of using a particular power vector, $\boldsymbol{P}(SF_i)$ for a group of links, and $l \in L$ assigned to the i-th subframe. As shown in Fig.8, magnitudes of the sum of power vectors assigned (with frequency, $\xi = 1$) by our optimization strategy to 4 subframes are 0.02mW, 0.01mW, 0.005mW, and 0.002mW. This also satisfies the constraint imposed in (14) where $\boldsymbol{P} = 0.037$mW (the admissible spectral mask in UWB communications = 0.039mW). This suggests that smaller values of ξ are suitable for real-time traffic. Higher power allocation (e.g., 0.02mW, 0.01mW) during the frame interval results in increased transmission range such that the nodes can reach the destination nodes in smaller number of hops.

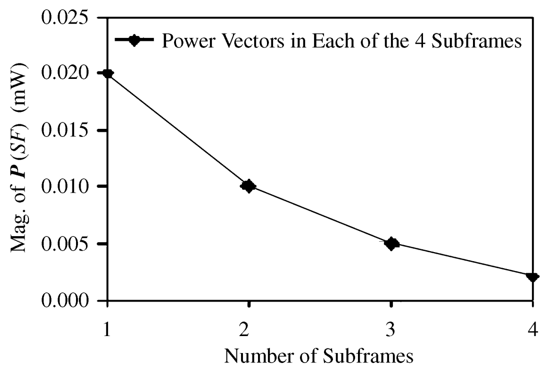

Fig.8. Magnitude of power vectors allocated in each subframe with unit frame interval.

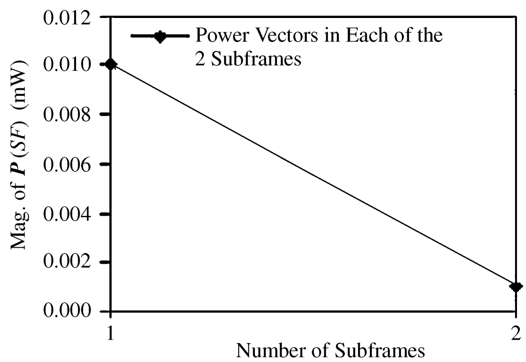

Fig.9. Magnitude of power vectors allocated in each subframe with frame interval=2units.

Fig.9 shows the scenario with 2 subframes with $\xi = 1$. Higher value of ξ indicates higher frequency of allocation of certain power vector, $\boldsymbol{P}(SF_i)$ for the i-th subframe. As shown in Fig.9, the magnitudes of power vectors allocated to 2 subframes are 0.01mW (frequency =3) and 0.001mW (frequency =7), much smaller in magnitude as compared to the scenario with $\xi = 0.5$. This indicates that higher values of ξ are suitable for delay tolerant non-real-time applications.

5.3 Priority Based Joint Link and Power Scheduling

Fig.10 depicts an important aspect of our optimization algorithm. Two applications, App. 1 and App. 3, has been enqueued twice for service requests. Thus according to (17), power assigned to these applications has been reduced for their second requests. This shows the unique design of our priority protocol. Additionally, since the power level for each of the slots assigned by the CR is quite high, it could accommodate only 6 slots in a frame. This is in tune with (19).

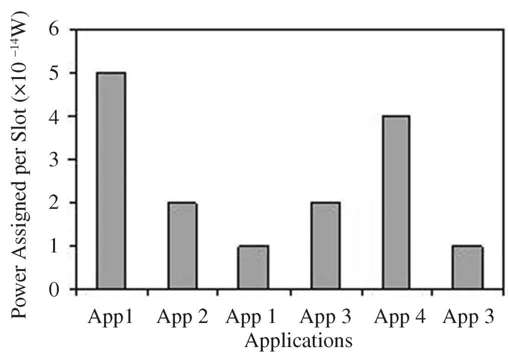

Fig.10. Power allocations for each application request in 6 time slots.

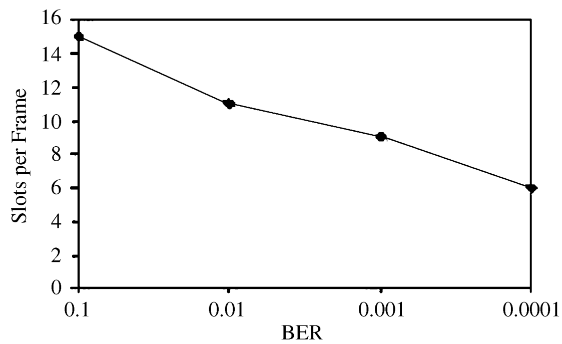

Fig.11. Number of slots assigned per frame for varying values of BER.

Fig.11 gives us an estimate of the scheduling algorithm performed by the CR based on the power constraints and the MAI observed at each node. As in (18), we observe that the signal power increases with improvement in BER values. So, increased power is assigned to each application with improvement in BER from 0.1 to 0.0001. This has a negative impact on the number of slots per frame. Higher signal power increases MAI among the transmitting nodes, which in turn restricts the number of parallel transmissions. Higher number of parallel transmissions (15 for BER of 0.1 as shown in Fig.11) is possible at higher values of BER which gradually decreases with improvement in BER values. The power allocations for the six slots assigned for BER of 0.0001 are also shown in Fig.10.

6 Conclusion

In this research, we have proposed a novel cross-layer based ROPAS architecture applicable for mobile UWB networks. The Rake optimization in our ROPAS receiver achieves minimal BER with an optimal selection of correlators in the MRC-based Rake receiver. The optimization also reduces the computation complexity by reducing the number of fingers selected for signal estimation and their corresponding weight coefficients. The CR-based cross-layer optimization of joint power control and link scheduling has been simulated in each mobile UWB node. Our proposed optimization algorithm is capable of allocating "free" channel bandwidth dynamically to requesting application within power constraints in finite frame intervals. Additionally, non-real time and real-time applications are differentiated by designing a novel queuing strategy in ROPAS which provides fairness and higher throughput among services with varying delay constraints in a mobile UWB network. The optimal division of a frame into slots is computed to support maximum number of parallel transmissions with dependence on parameters like the distance between transmitter-receiver pair and BER values. Finally, fairness among applications is taken care of while allocating power to each slot based on the frequency of request of a requesting application.

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