Optimal Power Control and Opportunistic Fair Scheduling in TH-PPM UWB Ad-hoc Multimedia Networks

Yang Liu[1,*], Yu-Kwong Kwok[1] and J. Wang[2]

[1]Department of Electrical and Electronic Engineering
The University of Hong Kong, Pokfulam Road, Hong Kong

[2]Department of Electronics, University of Kent, United Kingdom

Abstract**—***Ultra wideband (UWB) systems are widely envisioned to be the next important wireless infrastructure for efficient short-range communications and mobile applications. Indeed, forming ad hoc networks among various UWB enabled devices is considered as an important mobile data exchange operating environment. In our study, we explore the problem of jointly optimizing the power level and data rate used in the devices in such a UWB based ad hoc network. We propose a practical optimization scheme and decompose the optimization problem into power control for real-time applications and opportunistic scheduling for non-real-time applications. Efficient optimization algorithms are designed to meet different fairness requirements and numerical results are obtained.*

Keywords—optimal power control, opportunistic scheduling, TH-PPM UWB, multimedia, ad hoc networks, predefined fairness, proportional fairness.

1. Introduction

In this paper we present a joint power and data rate optimization scheme for time-hopping pulse position modulation (TH-PPM) ultra wideband (UWB) *ad hoc* multimedia networks with the coexistence of real-time (RT) and non-real-time (NRT) applications. UWB is characterized by its giga-hertz transmission bandwidth. Specifically, a TH-PPM UWB signal is limited in one nanosecond. As such, it is commonly called impulse radio, and different time shifts in the position of pulse are commonly used to denote the data symbols 0 and 1 [1], [6]. To eliminate catastrophic collisions in the multiple access control process, each UWB link uses a distinct pulse-shift pattern called a *TH code*. The use of impulse radio makes the system multi-path robust, well covert, and high rated. In addition, because UWB systems are simple in structure and can provide high data rates, *ad hoc* networking over UWB is widely considered as a perfect match for wireless personal area networks (WPANs).

As the interference caused by other links is related to users' power levels and data rates, we can employ a joint optimization scheme (power control and scheduling) taking into account multiple parameters when the node distribution is known. Related previous work can be found in [4], [5], [13]. Work in [5] focuses on the scheduling process when a new user gets access and considers the fairness for getting access in UWB ad hoc networks. On the other hand, work in [4] builds their findings on large number of simulations. One of the findings, which is in accordance with the work in [5], is that the link should transmit at peak power or keep silent to maximize throughput in a UWB network which contains only NRT links. In [13], the max-min fairness scheduling and power control problems are addressed by a dual approach. However, scenarios considered in the previous work are either all RT or all NRT. Indeed, none of the previous research efforts is for optimizing the system performance in a multimedia application environment, where both RT and NRT applications coexist. Furthermore, how to meet different fairness requirements (e.g., proportional fairness) in the scheduling of accessed NRT user group is not well addressed. Thus, there is a pressing need to explore further for the joint optimization in the UWB multimedia network.

Our proposed algorithm works by maximizing throughput while meeting the fairness requirement for NRT links and minimizing the power level of RT links. The QoS (quality of service) for both applications can then be simultaneously guaranteed.

This paper is organized as follows. In Section 2, a UWB *ad hoc* network model is presented and our joint optimization algorithm is introduced. This is followed by, in Section 3, the illustration of the optimization strategy when RT and NRT applications coexist. Section 4 presents the optimization results. Finally, Section 5 concludes this paper.

* Corresponding Author: Yang Liu; Email: *yangliu@eee.hku.hk*
This research was supported by a grant from the Research Grants Council of the HKSAR under project number HKU7157/04E.

1-4244-0270-0/06/$20.00 (c)2006 IEEE

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2006 proceedings.

2. Joint Optimization Algorithm Overview

2.1 Piconet structure

Our system is structured as a single piconet, in which all nodes are able to communicate with each other directly (i.e., a full mesh connection) and no routing is needed.

A typical piconet is shown in Fig. 1. A piconet controller (PNC) is defined for the association of new nodes (in this paper association is the process of making one single node known by the system) and disassociation for old nodes. Besides, PNC is in charge of channel access. Generally, the first node which sets up the piconet is considered default PNC. A specified TH code is assigned to PNC and used as pilot channel. Other TH codes are distributed to needed nodes by PNC as data channels. The separation of pilot channel and data channel will decrease the times of packet exchange. Therefore, the total acquisition time is reduced although the acquisition time is still fairly long. We do not consider the mobility of nodes.

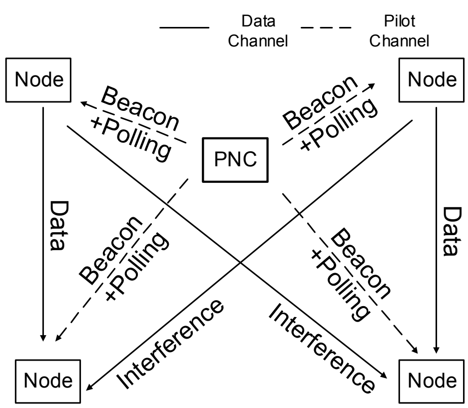

Fig. 1. Piconet structure.

2.2 Algorithm overview

Considering UWB signal's attenuation, we can denote the signal-to-interference-and-noise-ratio (*SINR*) at the *i*-th link's receiver in a given time slot as follows [5, 6]:

$$SINR_i = \frac{P_i g_{ii}}{R_i(\eta_i + T_f \sigma^2 \sum_{k=1,k\neq i}^{N} P_k g_{ki})}, i = 1,...,I \quad (1)$$

where I is the total number of links in the system (in the case where RT and NRT links coexist, I is sum of both links); P_i is the average power level of the *i*-th link; R_i is the average binary bit rate of the *i*-th link; g_{ij} is the corresponding path gain from the *i*-th link's transmitter to the *j*-th link's receiver; η_i is the background noise; T_f is the time space between two consecutive UWB pulses of one user, i.e., frame time; σ is an inter-user interference parameter depending on the shape of the mono-cycle.

The joint optimization algorithm is to be executed at the beginning of each time slot to tackle the various wireless channels. Although power control and scheduling should be considered for both RT and NRT links, the algorithm can be simplified if the property of applications is included.

For RT applications, each link is required to transmit at every time slot, which already defines the scheduling. As a contrast, for NRT applications, the power control process can be found according to the following assertion.

In the optimal power allocation for a UWB ad hoc multimedia network, each NRT link in a given time slot either sends at the maximum power or does not send any packet at all.

It should be noted that additional interference due to the access of RT links equals that of the case when the background noise increases [1], [2]. Therefore, the performance projection remains convex in every power dimension.

Accordingly, we have the transmission scenario of NRT links is limited by $2^M - 1$ where M is the number of NRT links (silent scenario is excluded). In each time slot, given a NRT transmission scenario, the RT links' power distribution will be examined if they can transmit under peak power after power control. If it is admissible, the data rate for each NRT link under the RT power distribution and the given NRT transmission scenario will be calculated. In addition, the weight for each NRT link will be available according to corresponding opportunistic scheduling strategy. Otherwise, the given NRT transmission scenario will be neglected. After all the NRT transmission scenarios pass the examination, the NRT links shall be scheduled to maximize the weighted rate sum and the optimization in the slot ends.

Therefore, the illustration to our optimization strategy can be divided into two parts: power control for RT links to minimize the interference (the sum of RT links' power) and scheduling for NRT links to meet the fairness requirements. Furthermore, according to whether there is predefined throughput share or not, the weight update for NRT case can be studied separately.

3. Joint Optimization Algorithm

3.1 Power control for RT links

Previous work in [9] proves that we can always find a distributed power control algorithm which converges exponentially fast to the (optimum) minimum power vector, if one exists, in a FDMA or TDMA cellular system. In this section we will show that this algorithm remains effective for RT links in our UWB ad hoc network.

One of the main results in [9] is an iteration algorithm in uplink power control for the *i*-th link in time slot *L*:

$$P_i(L) = \frac{\beta}{SINR_i(L-1)} P_i(L-1) \qquad (2)$$

where β is the predefined *SINR* threshold that depends on the acceptable bit error rate.

Proposition: For RT links in the UWB multimedia ad hoc network, the distributed power control algorithm in (2) converges exponentially fast to the minimum power vector, if one exists.

The proof to the proposition can be done based on the comparison of our problem structure to the power control situation in [8].

In addition, due to the peak power constraint condition, the iteration algorithm could be adopted with a small modification, again similar to the work in [8]:

$$P_i(L) = \min\left[\frac{\beta}{SINR_i(L-1)} P_i(L-1), P_{\max}\right] \qquad (3)$$

where min[*a* , *b*] returns the smaller number of *a* and *b* and $P_{\max}$ is the peak power.

3.2 Scheduling for NRT links with predefined throughput share

In a given time slot, the scheduling problem for NRT links meeting our optimization rule may be formalized as follows:

Maximize $\sum_{j=1}^{M} Y_j$ (4) subject to the constraint:

$$\prod_{j=1}^{M} Q_j \prod_{j=1}^{M} (Q_j - Q_{\max}) = 0 \qquad (5)$$

where $SINR_j \geq \beta$, (6)

and Y_j is NRT link *j*'s long run expected throughput.

Given corresponding target weights ϕ_j and ϕ_k in the system, for any two NRT links *j* and *k*, the predefined fairness can be defined as:

$$\frac{Y_j}{\phi_j} = \frac{Y_k}{\phi_k} \qquad (7)$$

With the predefined fairness, as shown in [10], the scheduling problem is equivalent to

Maximize $\sum_{j=1}^{M} \omega_j Y_j$ (8) subject to the constraints (4) – (5), where ω_j is a non-negative constant to be found.

In [10] the stochastic approximation algorithm is adopted to update the weight matrix to satisfy deterministic fairness over multiple wireless channels. This approximation is an effective technique for finding roots of a function $f(\cdot)$ whose explicit expression is not known. The stochastic approximation reveals the root for $f(\cdot)$ at step *L*, which is denoted by $x(L)$, and will satisfy:

$$x(L) = x(L-1) - a(L-1) \times y(L-1) \qquad (9)$$

where $a(L)$ is the step size, $y(L) = f(x(L)) + e(L)$ is the noisy measurement of $f(\cdot)$ and $e(L)$ is the observed noise. If $e(L)$ is white noise and $a(L)$ converges to zero, under certain conditions, $x(L)$ will definitely converge to the root of $f(\cdot)$. Recall that our scheduling problem is similar to that in [10], stochastic approximation will work in the process of NRT links' power distribution.

In our case, $f(\cdot)$ is defined by $f(\vec{\omega}) = [f_1(\vec{\omega}), ..., f_M(\vec{\omega})]$ where:

$$f_j(\vec{\omega}) = \frac{X_j(L)}{\sum_{j=1}^{M} X_j(L)} - \frac{\phi_j}{\sum_{j=1}^{M} \phi_j} \qquad (10)$$

and $\vec{\omega} = [\omega_1, ..., \omega_M]$ is the adaptive weight vector. Our scheduling problem is now equivalent to finding the roots of $f_j(\vec{\omega}) = 0$. Using stochastic approximation, the noisy observation of $f_j(\vec{\omega})$ can be found by $y_j(L)$ where:

$$y_j(L) = \frac{X_j(L)}{\sum_{j=1}^{M} X_j(L)} - \frac{\phi_j}{\sum_{j=1}^{M} \phi_j} \qquad (11)$$

and the expected value of the observation error is:

$$E(e(L)) = E(y_j(L) - f_j(\vec{\omega})) = 0 \qquad (12)$$

Thus, the weight matrix $\vec{\omega}$ can be found by:

$$\omega_j(L) = \omega_j(L-1) - a(L-1) \times y_j(L-1) \qquad (13)$$

In (13) $a(L)$ should be chosen to converge to zero, and in our case, $a(L) = 1/L$ is sufficient. It is noticeable that our design of weight update process is different from that in [10], where $y_j(L) = \frac{\phi_j}{\sum_{j=1}^{M} \phi_j} - \frac{X_j(L)}{\sum_{j=1}^{M} X_j(L)}$.

Since ω_j is expected to denote the long term share for NRT links, it should decrease when the assigned resource is redundant ($y_j(L) > 0$) and increase when the resource is insufficient ($y_j(L) < 0$). The numerical results prove that our method performs better than the original design in the weight convergence process.

3.3 Scheduling for NRT links without predefined throughput share

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2006 proceedings.

Since there is no fairness requirement in this case, we want to allocate as much as possible resource to the link with better channel conditions and hold the impairment to the worse channel links under an acceptable limit. Interestingly this target is similar to proportional fairness in [4]. A natural idea to achieve best proportional fairness is to find the NRT links' transmission scenario which maximizes $\sum_{j=1}^{M}\log(Y_j)$. However, this measurement will definitely decrease the throughput, which is in contradiction to our optimization rule formalized by (4). Therefore, we present a flexible scheduling algorithm to achieve a tradeoff between proportional fairness and throughput. Although we cannot prove that the strategy is optimal, we will show that it is a quite close approach.

Enlightened by our previous work in [15], current approach tries to maximize the throughput $\sum_{j=1}^{M} R_j'$ where R_j' is the updated data rate in the given time slot. The algorithm is shown as follows:

$$R_j' = \begin{cases} R_j & Y_j \geq Y_w \\ R_j \times \dfrac{Y_w}{Y_j} & others \end{cases} \quad (14)$$

where $Y_w = \max(R_j) \times f$ and $0 \leq f \leq 1$ is a flexible parameter controlling the extent to tradeoff.

Since this algorithm uses weighted data rate to increase proportional fairness, PW (proportional weighted) can be used to characterize it in contrast to WS (weighted sum) algorithm in the previous section.

4. Simulation Results

4.1 Performance metrics

Besides RT power (*P*) and NRT throughput (*Y*) mentioned above, two other long run metrics, fairness index (*F*) and usage function (*U*) are used. In the predefined fairness case, fairness index can be denoted by:

$$F = \frac{\left[\sum_{m=1}^{M}(Y_m/\phi_m)\right]^2}{M\sum_{m=1}^{M}(Y_m/\phi_m)^2} \quad (15)$$

where ϕ_m is the corresponding share for NRT link *m*. As a contrast, a usage function is defined by the logarithm sum of throughput $U = \sum_{j=1}^{M}\log(Y_j)$ to evaluate the proportional fairness when there is no predefined fairness constraint.

4.2 Simulation parameters

For TH-PPM modulations, T_f is fixed at 10 nanoseconds in our simulation. Therefore, the maximum data rate constraint is $R_{\max} = 1/T_f = 100Mbps$. In all scenarios the data rate of RT link is fixed at $S = R_{\max}/2$ .Other system parameters are valued as those in [5]. The ratio between the peak power and the background noise power is 2×10^{20} and the background noise power is assumed the same for every link where $\eta = 2.568\times10^{-21}V^2s$. A required *SINR* at the receiver end is fixed at 30 (14.7dB). For NRT links, we assume that packets arrive according to a Poisson distribution with aggregate rate λ packets/ms. Therefore, the inter-arrival time will be $1/\lambda$.

The UWB propagation model is described by path loss, shadowing and multi-path, and can be denoted by:

$$g = r^{-\delta}\times10^{\upsilon/10}\times\zeta \quad (16)$$

where r is the distance between the transmitter and the receiver, $\delta = 4$ is the path loss decay factor, and the shadowing factor υ is a Gaussian random variable with mean zero and deviation $\sigma_s = 8dB$. In addition, the multi-path effect ζ is described by the modified Saleh-Valenzuel (S-V) model [2] where four sets of parameters have been found. The second set (CM2), based on NLOS (0-4m) channel measurements, is used in our simulation since it is a tradeoff between LOS(0-4m) and LOS(4-10m). We assume that all multi-path signals are collected.

Statistics in [6] show that the node number should be less than 10 in a high data rate (over 100 Mbps) TH-PPM UWB system. Therefore, we assume that the total number of nodes is around 10 and the link number (N+M) is around 5. All the nodes are distributed uniformly and randomly in an area of $11m\times11m$. Different combinations of N and M are adopted to study the optimization results. Specifically, (N, M) = (0, 4), (1, 4) are adopted in simulations independently to show how the increase of RT users affects the optimization result. Besides, (N, M) = (2, 3), (1, 4) are used to reveal that the optimization varies in a fixed size network with different RT and NRT combinations. In the scheduling of predefined fairness scenario, for M = 4, $\phi = (0.25, 0.25, 0.25, 0.25)$ is set for the uniform share case. In the uniform case, the initial

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2006 proceedings.

value of iteration for each element in the weight matrix ω is 2.

The rate and power adaptation period is set as T =2ms. Path loss and shadowing are assumed constant in each adaptation period and the multi-path fading is averaged over n_s times (n_s is assumed to be four in our calculation). In each simulation 1000 frames are generated, i.e., simulation time is 2s.

4.3 Simulation results

In this section, we report the main results obtained from the joint optimization strategies. In addition we shall compare some performance to that in MT (maximum throughput) and MU (maximum usage function, i.e., maximum proportional fairness) strategies.

Firstly, we show the long run power iteration result with (N, M) = (1, 4) and (2, 3). Fig. 2 shows that the power distributions in both scenarios do not vary evidently when inter-arrival time increases. That is, when traffic load varies, RT link will remain a relatively stable power level since the interference from NRT links are caused by different combinations of attenuated peak powers. Furthermore, the large gap between the two scenarios reveals that NRT link is the main interference source to RT links. The decrease of NRT number is not only helpful to reduce the power level of RT links, but also will benefit the total throughput since interference from RT links is reduced.

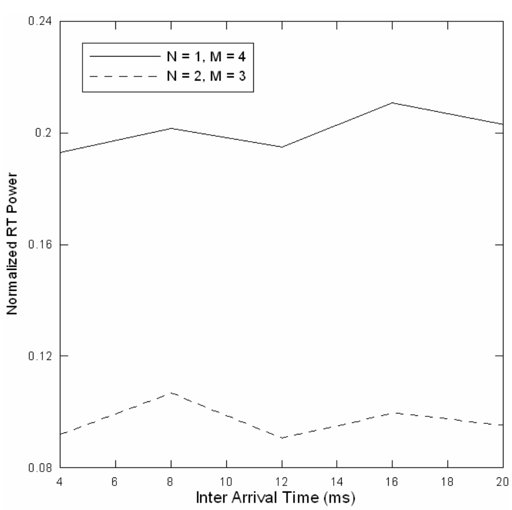

Fig.2. Normalized RT power level.

Secondly, scheduling behaviors with uniform predefined fairness requirement are observed from Fig. 3 and Fig. 4. In all the three scenarios shown in both figures, as expected, our WS strategy outperforms MT in fairness evidently while maintaining almost the same throughput. It is noticeable that whether the network size is enlarged or not, the introduction of RT links will require a smaller optimized traffic load to achieve maximum throughput. On the other hand, this introduction will decrease fairness between NRT links but increase fairness improvement compared to that in MT case. The more the number of RT links is, the more unfair will be caused in the network. Therefore, our WS algorithm is quite effective to improve the fairness when needed most.

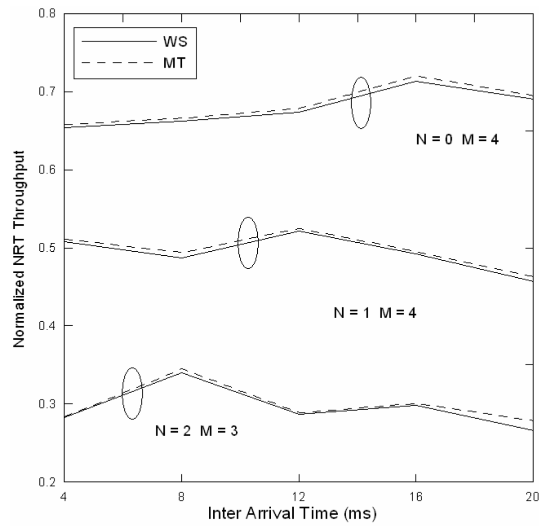

Fig. 3. Normalized NRT throughput with uniform predefined fairness.

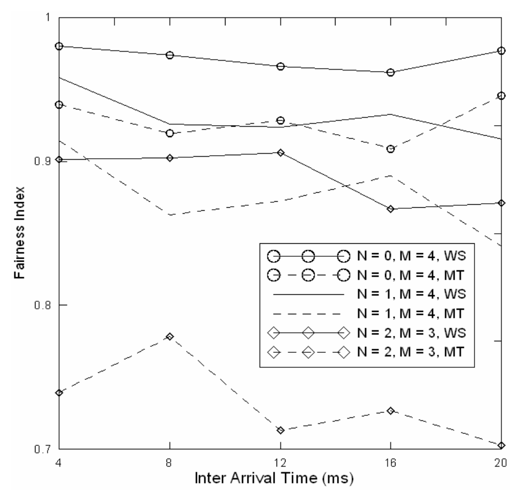

Fig. 4. Fairness index with uniform predefined fairness.

Finally, we demonstrate the behavior of PW scheduling when there is no predefined fairness share. The result of MT and MU is used as normalized reference in Fig. 5 and Fig. 6 separately. As expected, Fig. 5 and Fig. 6 show that PW achieves tradeoff between MT and MU. Furthermore, the adjustable parameter f successfully controls the tradeoff extent. To achieve a relatively high throughput while keeping a good proportional fairness, f = 0.4 seems to be proper for (N, M) = (2, 4). Since PW tries to improve those links whose data rates are under f times

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2006 proceedings.

of the maximum data rate in current slot, our algorithm is surely adaptable in different network scenarios and surrounding configurations (interested readers may refer to the adaptation study in our previous work in [15]). Therefore, in practical situations, f should be fixed at 0.4 unless specified requirement is found.

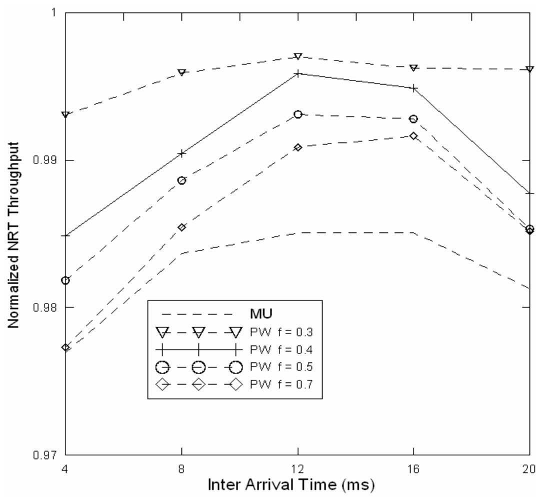

Fig. 5. Normalized NRT throughput for N=2, M=4 without predefined fairness.

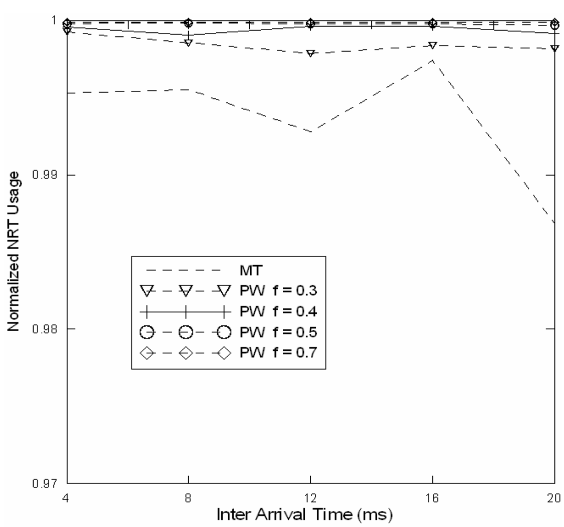

Fig. 6. Normalized usage function for N=2, M=4 without predefined fairness.

5. Conclusions

We have presented a joint power and rate optimization method for UWB ad hoc multimedia network. The proposed strategy tries to maximize system throughput while meeting the fairness requirement for NRT links and minimizing the power level of RT links. Simultaneously the required *SINR* for both applications are guaranteed. For NRT links, two scheduling strategies characterized by WS and PW are designed. The former strategy intends to achieve predefined fairness among NRT links while the latter one is a good tradeoff between proportional fairness and throughput. Since our work is limited in a small area piconet scenario, the optimization can be done through searching all possible cases. However, when the network scale increases, this search may consume large time and become low efficient. Therefore, a feasible measurement to speed up the optimization may be a hierarchy approach [12] in the future.

References

[1] [Online]. Available: http:// www.UWB.org.

[2] J. Foerster, "Channel Modeling Sub-committee Report Final," *IEEE P802.15-02/490r1-SG3a*, Feb. 2003.

[3] D. Helal and P. Rouzet, "STMicroelectronics Proposal for IEEE 802.15.3a Alt PHY," *IEEE P802.15-02/372r8*, July 2003.

[4] B. Radunovic and J.-Y. Le Boudec, "Optimal Power Control, Scheduling, and Routing in UWB Networks," *IEEE J. Select. Areas in Comm.*, vol. 22, no.7, pp. 1252–1270, Sept. 2004.

[5] F. Cuomo, C. Martello, A. Baiocchi and F. Capriotti, "Radio Resource Sharing for Ad-hoc Networking with UWB," *IEEE J. Select. Areas in Comm.*, vol. 20, no. 9, pp. 1722–1732, Dec. 2002.

[6] M. Z. Win and R. A. Scholtz, "Ultra-wide Bandwidth Time-hopping Spread-spectrum Impulse Radio for Wireless Multiple-access Communications," *IEEE Trans. Comm.*, vol. 48, no. 4, pp. 679–689, Apr. 2000.

[7] F. Kelly, "Charging and Rate Control for Elastic Traffic," *European Trans. on Telecommunications*, vol. 9, pp. 33–37, 1997.

[8] T. Elbatt and A. Ephremides, "Joint Scheduling and Power Control for Wireless Ad Hoc Networks," *IEEE Trans. Comm .*, vol. 3, no. 1, pp. 74–85, Jan. 2004.

[9] G. Foschini and Z. Miljanic, "A Simple Distributed Autonomous Power Control Algorithm and Its Convergence," *IEEE Trans. Veh. Technol.*, vol. 42, no. 4, pp. 641–646, Nov. 1993.

[10] Y. Liu and E. Knightly, "Opportunistic Fair Scheduling over Multiple Wireless Channels," *Proc. IEEE INFOCOM 2003,* vol. 2, pp. 1106–1115, Apr. 2003.

[11] X. Liu, E. Chong and N. Shroff, "Transmission Scheduling for Efficient Wireless Network Utilization," *Proc. IEEE INFOCOM 2001,* pp. 776–785, 2001.

[12] R. L. Cruz and A. V. Santhanam, "Optimal Routing, Link Scheduling and Power Control in Multi-hop Wireless Networks," *Proc. IEEE INFOCOM 2003,* pp. 702–711, 2003.

[13] R. Negi and A. Rajeswaran, "Scheduling and Power Adaptation for Networks in the Ultra Wide Band Regime," *Proc. IEEE GLOBECOM 2004*, vol. 1, pp. 139–145, Nov. – Dec. 2004.

[14] Y. Liu and E. Knightly, "WCFQ: An Opportunistic Wireless Scheduler with Statistical Fairness Bounds," *IEEE Trans. on Wireless Comm.,* vol. 2, issue 5, pp. 1017–1028, Sept. 2003.

[15] Y. Liu, Y.-K. Kwok and J. Wang, "An Environment Adaptive Practical Packet Scheduling Algorithm with Single User Fairness Guarantee over the Forward Link of 3G Cellular Data Services," *Proc. IEEE WWAN 2005*, pp. 878–882, 2005.

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2006 proceedings.