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Throughput Optimization for UWB-Based Ad-Hoc Networks

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1. Introduction

The increasing demand for portable, high data-rate communications has stimulated search for new wireless technologies. Ultra-wideband impulse radio (UWB-IR) is an emerging radio technology that can support data rates of megabit-per-second, while maintaining low average-power consumption. UWB uses very short, carrier-less pulses of bandwidth on the order of a few Gigahertz. Over the past decade, many individuals and corporations began asking the United States Federal Communications Commission (FCC) for permission to operate unlicensed UWB systems concurrent with existing narrowband signals. In 2002, the FCC decided to change the rules to allow UWB system operation in a broad range of frequencies between 3.1 and 10.6 GHz. The FCC defines UWB as a signal with either a *fractional bandwidth* of 20% of the center frequency or 500 MHz (when the center frequency is above 6 GHz). The formula proposed by the FCC commission for calculating the fractional bandwidth is $2(f_H - f_L)/(f_H + f_L)$ where f_H represents the upper frequency of the -10 dB emission limit and f_L represents the lower frequency limit of the -10 dB emission limit. What makes UWB systems unique is their large instantaneous bandwidth and the potential for very simple implementations. Additionally, the wide bandwidth and potential for low-cost digital design enable a single system to operate in different modes as a communications device, radar, or locator. Taken together, these properties give UWB systems a clear technical advantage over other more conventional approaches in high multipath environments at low to medium data rates. Communication over UWB is particularly attractive due to its wide range of bit-rates, resilience to multi-path fading, accurate ranging ability, low transmission power requirements, and low probability of interception. After substantial progress in research on the UWB physical layer, in recent years, researchers began to consider the design of UWB networks [1]-[9]. The maximum allowable UWB transmission power is limited to a very small value, since UWB shares the same frequency band with other existing wireless communication systems. Consequently, short-distance communications are the main uses considered and UWB networks will likely often be ad hoc in nature. In an ad-hoc network each node has to have a routing function and it is essential to use multihop transmission to reach nodes further away. Since each node has a network control function, even if one of the nodes is not working properly, its influence on the whole network is quite limited. Therefore, ad-hoc networks are excellent with respect to robustness. Ad-hoc network do not require any infrastructure, a feature which allows for instant deployment and rerouting of traffic around failed or congested nodes. Since in ad-

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hoc networks it is unnecessary to deploy base stations, the cost of a ad-hoc networks system is expected to be considerably lower than the corresponding cost of a cellular infrastructure. Furthermore, fault-tolerance (for example, due to richness of alternative routes ^[15]) of this type of networks is also significantly improved. Ad-hoc networks can be reconfigured to adapt its operation in diverse network environments. As the results of these characteristics, ad-hoc networks became of interest to the commercial and to the military markets. It is expected that UWB ad-hoc networks will be used for digital household electric appliances and peripheral equipment of PCs, for example, such as a wireless link between a PC and DVD player or a physical layer for a 'wireless USB' replacing traditional USB cables between devices. Examples of other applications that were considered are for networking among students in classrooms or among delegates at a convention centre. The mechanisms to best meet the requirements of the network layer for wireless ad hoc networks are a focus of current research and are certainly not well understood for UWB, which is a nascent networking technology. There are opportunities to leverage both radio link characteristics, using cross-layer design, and application requirements to optimize network layer protocols. For example, UWB devices in an ad hoc network may self-organize themselves into hierarchical clusters in ways that consider mutual interference, power conservation, and application connectivity requirements.

Throughput, which is defined as the bit rate of successfully received data, is a key performance measure for a data communication networks. In a wireless ad hoc network, throughput is a function of various factors, including the transmission power, the symbol rate (i.e., data rate), the modulation and the coding schemes, the network size, the antenna directionality, the noise and the interference characteristics, the routing and the multiple access control (MAC) schemes, and numerous other parameters. How to allocate resource and determine the optimal transmission power, transmission rate and schedule is a very challenging issue. There are several related papers ^{[2]-[8]} in the technical literature that study the throughput capacity and the optimization of UWB networks. They have suggested that: (1) an exclusion region around a destination should be established, where nodes inside the exclusion region do not transmit and the nodes outside the exclusion region can transmit in parallel ^[4], (2) the optimal size of the exclusion region depends only on the path-loss exponent, the background noise level, and the cross-correlations factor ^[6], (3) each node should either transmit with full power or not transmit at all ^[7], (4) the design of MAC is independent of the choice of a routing scheme ^[5].

In this chapter, we analyze and investigate the maximal total network throughput of UWB based ad hoc wireless networks. Understanding how this characteristic affects system performance and design is critical to making informed engineering design decisions regarding UWB implementation. The objectives of our work are: (1) to obtain theoretical results which demonstrate the dependencies among the maximum achievable throughput of a network, the number of active links in the network, the bit rate and the transmission power of active links, and other parameters, and (2) to determine the implications of these dependencies on the allocation and scheduling of the network resources. Our analysis show that the optimal allocation should: (1) allow the transmitters to either transmit at maximum power or be turned off, (2) allow more than one transmission when the maximum powers of the links are less than some value, which we term the critical power, (3) allow only one transmission when the maximum powers of the links are larger than the critical power, and (4) adjust the transmission rates to maintain the optimal transmission rates. We also derive an expression of the optimum transmission rate. As an example, we analytically calculate

the critical transmission power for the case of two-links and for the case of a scenario of N -links. Our results imply that the design of the optimal MAC scheme is not independent of the choice of the routing scheme. Furthermore, we expect our results obtain in this chapter to be helpful to network protocol design as well.

This chapter is organized as follows. The next section describes the UWB transmission system and formalizes the throughput optimization problem. In Section 3, we demonstrate the solution for the case of two simultaneous transmitters, while in Section 4 we analyze a network with arbitrary number of transmitters. Section 5 discusses the implications of the results, and the summary is given in Section 6.

2. Analytical model

We consider an ad hoc wireless network (Fig. 1.) that consists of identical nodes, each equipped with a half-duplex UWB radio. A transmitting node (a source node) is associated with a single receiver node (a destination node) and a pair of source-destination nodes forms a communication link. Each link can be selected for transmission by the MAC protocol based on some traffic requirements.

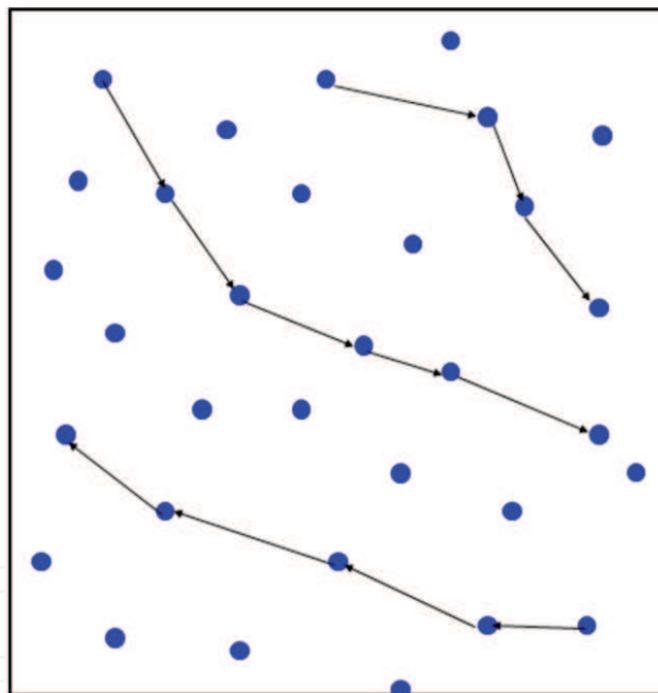


Fig. 1. A Multiple Hop Ad Hoc Network

We assume that the physical link layer is based on the *Time Hopping with Pulse Position Modulation* (TH-PPM) scheme, described in refs. [10--12]. In PPM, each monocycle pulse occupies a *frame*. Signal information is contained in pulse time position relative to the frame boundaries. Each bit is represented as L PPM-modulated pulses. An analytic TH-PPM representation of the transmitted signal of the k -th node is given by

$$s^k(t) = \sum_j w(t - jT_f - c_j^k T_c - \delta D_{[j/L]}^k) \quad (1)$$

where $w(t)$ denotes the monocycle pulse waveform, T_f is the nominal frame or pulse repetition interval, c^k_j is a user-unique pseudorandom TH code sequence (used for multiple access), T_c is the TH code chip period, $D^k_{\lfloor j/L \rfloor}$ is the k -th user's $\lfloor j/L \rfloor$ -th data symbol, where $\lfloor j/L \rfloor$ is the integer part of j/L and a symbol is transmitted as L monocycles PPM-modulated pulses, and δ is the amount of time shift of the PPM pulse for a data bit of "1".

The UWB communication system considered in this chapter is a spread-spectrum communication system, which uses a multiple-access scheme. Time hopping is used for multiple accesses. The source and the destination of each link have a common pseudorandom time hopping sequence, which is independent of other links' sequences. In the multiple-access scheme, transmissions on other links contribute added interference to the received signal and, due to randomness in time-hopping codes, we model such an interference as having statistical properties of Gaussian noise. The total noise at a receiver is comprised of background noise and a sum of interferences from all other active transmitters. The communication channel is assumed to be an AWGN channel. Thus, supposing that N links are active at a given time, the signal-to-interference plus noise (SINR) at the i -th link's receiver is represented as γ_i and is defined as [10]

$$\gamma_i = \frac{p_i g_{ii}}{R_i T_f \left(\eta_i + \rho \sum_{k=1, k \neq i}^N p_k g_{ki} \right)} \quad (2)$$

where R_i is the data transmission rate of i -th link and $R_i = 1/(LT_f)$, p_i is the average transmission power of the i -th link's transmitter, g_{ij} denotes path gain from the i -th link's transmitter to j -th link's receiver (g_{ii} is referred to as the i -th link's path gain and g_{ij} ($i \neq j$) is the interference path gain), η_i denotes the power of the background noise at i -th link's receiver, and ρ represents a parameter which depends on the shape of impulse((79) in ref. [10]).

In this work, a link is comprised of a pair of transmitter and receiver and the link is active if it is transmitting. When N links in a network are active at a given time, we define the throughput of the i -th link as the number of packets per second received without error at the i -th link's receiver:

$$T_i^N = R_i f(\gamma_i) \quad (3)$$

where $f(\gamma_i)$ is the packet success rate; i.e., it is the probability that the i -th link's receiver decodes a data packet correctly as a function of γ_i . The actual form of $f(\gamma_i)$ depends on the UWB receiver's configuration, the packet size, the channel coding, and the radio propagation model. We do not impose any restrictions on the form of $f(\gamma_i)$, except that $f(\gamma_i)$ is a smooth monotonically increasing function of γ_i , and $0 \leq f(\gamma_i) \leq 1$.

The total network throughput of N active links in the network, which we term T^N , is the sum of the N individual throughputs T_i^N .

$$T^N = \sum_{i=1}^N T_i^N \quad (4)$$

The aim of our optimization study is to determine the rate and the power assignments among the N links when the link gains and the background noise are given such that the total network throughput is maximized.

First we examine the properties of the throughput of link i , T_i^N , as a function of SINR. Using the following definition:

$$\mu_i = \frac{p_i \mathcal{G}_{ii}}{T_f \left(\eta_i + \rho \sum_{k=1, k \neq i}^N p_k \mathcal{G}_{ki} \right)} \quad (5)$$

eqs. (1) and (3) can now be represented respectively as

$$\gamma_i = \frac{\mu_i}{R_i} \quad (6)$$

$$T_i^N = \mu_i \frac{f(\gamma_i)}{\gamma_i} \quad (7)$$

Given the links' powers p_i ($i=1, \dots, N$), the value of μ_i is fixed and SINR γ_i varies only with rate R_i . As the rate R_i increases, the SINR γ_i and the packet success rate $f(\gamma_i)$ decrease. From eq. (7), we can see that too large or too small SINR leads to reduced throughput; at small SINR, the throughput is limited by small packet transmission success probability; however, at large SINR, the throughput is limited by small data transmission rate. Thus, we expect that there is an optimal value of SINR or an optimal symbol rate which corresponds to the maximum throughput.

3. Optimization for the two-links case

Before analyzing the performance of an arbitrary number of active links, we examine the case of two active links ($N=2$). This will allow us to gain some insight into the optimum allocation of transmission rates and transmission powers based on maximization of the throughput.

In the case of two active links, the total throughput is

$$T^2 = \mu_1 \frac{f(\gamma_1)}{\gamma_1} + \mu_2 \frac{f(\gamma_2)}{\gamma_2} \quad (8)$$

To obtain the optimal values of SINRs, γ_1^* and γ_2^* , that maximize the total network throughput, when p_1 and p_2 are fixed, we differentiate eq. (8) with respect to γ_1 and γ_2 , setting the first derivatives at zero and verifying that the second derivatives are negative. A simple calculation reveals that the conditions for both γ_1^* and γ_2^* are the same and, therefore, we can write $\gamma_1^* = \gamma_2^* = \gamma_c$ and state the conditions on γ_c as follows:

$$f(\gamma_c) = \gamma_c f'(\gamma_c) \quad (9)$$

$$f''(\gamma_c) < 0 \quad (10)$$

Then, from eq. (6), we calculate the optimal data rates:

$$\begin{aligned}
 R_1^* &= \frac{\mu_1}{\gamma_c} = \frac{1}{\gamma_c T_f} \cdot \frac{g_{11} p_1}{\eta_1 + \rho g_{21} p_2} \\
 R_2^* &= \frac{\mu_2}{\gamma_c} = \frac{1}{\gamma_c T_f} \cdot \frac{g_{22} p_2}{\eta_2 + \rho g_{12} p_1}
 \end{aligned}
 \tag{11}$$

And with the above conditions, the optimal total network throughput is

$$\begin{aligned}
 T^{2*} &= f'(\gamma_c)(\mu_1 + \mu_2) \\
 &= \frac{f'(\gamma_c)}{T_f} \left(\frac{g_{11} p_1}{\eta_1 + \rho g_{21} p_2} + \frac{g_{22} p_2}{\eta_2 + \rho g_{12} p_1} \right)
 \end{aligned}
 \tag{12}$$

When there is only a single active link in the network, either $p_2=0$ or $p_1=0$, the optimum total throughput is, respectively

$$\begin{aligned}
 T_1^{1*} &= T^{2*}(p_2=0) = \frac{f'(\gamma_c)}{T_f} \cdot \frac{g_{11} p_1}{\eta_1} \\
 T_2^{1*} &= T^{2*}(p_1=0) = \frac{f'(\gamma_c)}{T_f} \cdot \frac{g_{22} p_2}{\eta_2}
 \end{aligned}
 \tag{13}$$

If we can adapt the transmission rates to the transmission powers according to eq. (11), the optimal total network throughput is then a function of the two links' powers and its value is determined by eqs. (12) and (13). Next, we show how to allocate the transmission powers between the two links so as to maximize the total network throughput. To do so, we focus our attention on eq. (12). From eq. (12), the optimal total network throughput is a function of p_2 only for fixed value of p_1 . In Figure 2, we depict a set of curves of the optimal total network throughput for different values of p_1 . Note that the graph includes the value of T_2^{1*} (i.e., $T^{2*}(p_1=0)$) and that the values for $p_2=0$ correspond to the situation in which only the first link is active. We state two observations: Firstly, we note that the throughput increases for large enough values of p_2 and that for small values of p_1 , the value of T^{2*} increases faster than for larger values of p_1 , so that T_2^{1*} will eventually exceed T^{2*} for non-zero p_1 . Secondly, we observe from the Figure that, there is a critical value, p_{c1} , such that if p_1 is larger than p_{c1} , T^{2*} will first decrease, take on a minimum, and then increase as p_2 grows. However, if p_1 is smaller than p_{c1} , T^{2*} will always be an increasing function of p_2 , with a minimum at $p_2=0$ (i.e., when the second link is inactive). These two observations imply that, when the two powers are high enough, the optimal total network throughput of two active links will always be smaller than the throughput of a single active link, but if the power of the first link is smaller than p_{c1} , then the adding of the second link increases the optimal total network throughput. To obtain the value of p_{c1} , we set $\partial T^{2*} / \partial p_2$ at $p_2=0$ at zero, which results in

$$p_{c1} = \frac{\eta_2}{2\rho g_{12}} \left(\sqrt{1 + 4 \frac{\eta_1^2 g_{12} g_{22}}{\eta_2^2 g_{21} g_{11}}} - 1 \right)
 \tag{14}$$

Also, if eq. (12) is seen as a function of single variable p_1 with p_2 being a parameter, we can obtain the critical value of p_2 as

$$p_{c2} = \frac{\eta_1}{2\rho g_{21}} \left(\sqrt{1 + 4 \frac{\eta_2^2 g_{21} g_{11}}{\eta_1^2 g_{12} g_{22}}} - 1 \right) \quad (15)$$

When p_2 is smaller than p_{c2} , T^* will always be an increasing function of p_1 . If the power p_1 and p_2 simultaneously satisfy the following two inequalities: $p_1 < p_{c1}$ and $p_2 < p_{c2}$, then the total network throughput, T^* , is larger than the throughputs of the single active link case with the same power, T_1^{1*} and T_2^{1*} . In the example of Figure 2, we find that $p_{c1}=90.95$ mW and $p_{c2}=155.69$ mW.

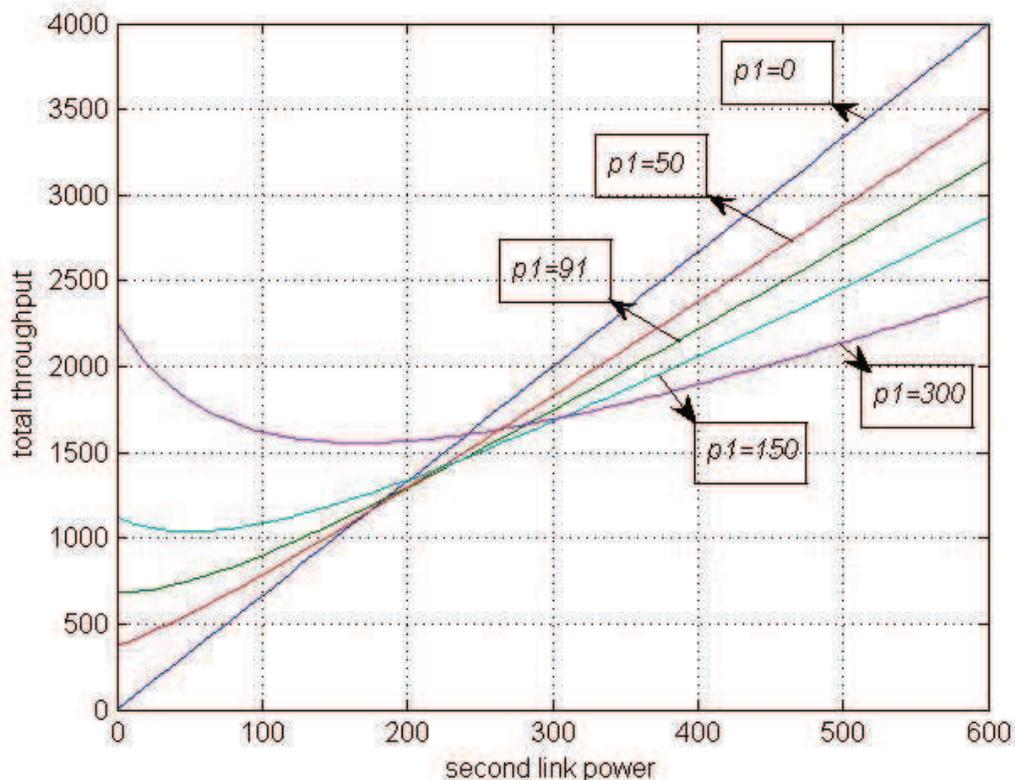


Fig. 2. The maximal total throughput vs. the power of the second link, the power of the first link as the parameter, and with the following values of parameters in (12): $f(\gamma_c)/T_f=1$ bit/s, $g_{11}=0.03$, $g_{22}=0.04$, $g_{21}=0.003$, $g_{12}=0.002$, $\rho=0.01$, $\eta_1=0.004$ mW, $\eta_2=0.006$ mW, $p_{c1}=90.95$ mW, $p_{c2}=155.69$ mW

In any practical situation, transmission powers are not unlimited. But, using eq. (11), we can calculate the corresponding optimal transmission rates according to the attainable transmission power values and, so as to achieve the optimal throughput. We describe how to allocate the transmission powers, so as to maximize the throughput, when $0 < p_1 < P_1$ and $0 < p_2 < P_2$. Since the sign of the second derivatives of eq. (12) with respect to p_1 and p_2 is positive for any value of p_1 and p_2 , the maximum throughput lies on the boundary of the attainable region, i.e., $[0 < p_1 < P_1, 0 < p_2 < P_2]$. Based on our analytic results obtained so far, if $P_1 < p_{c1}$ and $P_2 < p_{c2}$, the optimum transmission power allocation is $p_1=P_1$ and $p_2=P_2$, i.e., the two links' transmitters transmit at their maximum powers and at the same time (Figure 3 is an example of such a case). However, if $P_1 > p_{c1}$ and $P_2 > p_{c2}$, the optimum allocation is $p_1=P_1$, $p_2=0$ or $p_1=0$, $p_2=P_2$, i.e., the transmitter of one link transmits at its maximum power, while the other is turned off (Figure 4 is an example of such a case).

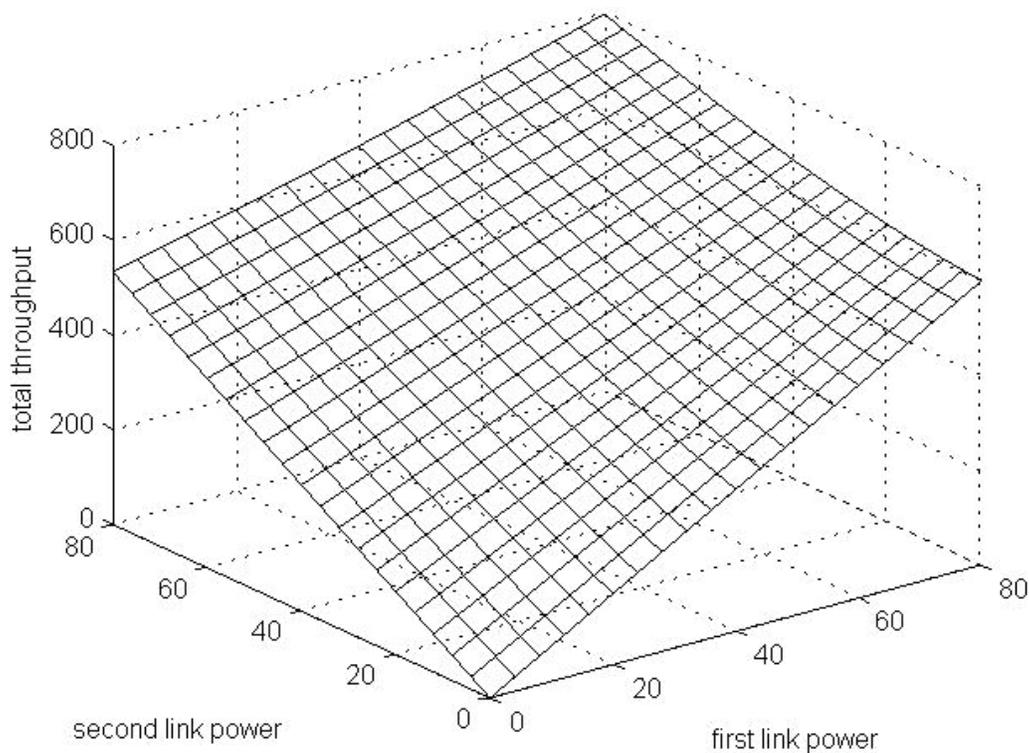


Fig. 3. The maximal total throughput vs. the transmission powers of the two link, when maximum attainable powers are smaller than the critical values, for the same parameters' values as in Figure 2 (the total throughput is maximum at $p_1=80$ mW, $p_2=80$ mW)

A transmitted signal attenuates according to a power law as a function of distance from its transmitter; i.e., if d_{ij} is the distance from the i -th link's transmitter to j -th link's receiver, then

$$g_{ij} = c \cdot d_{ij}^{-\alpha} \quad (16)$$

where c and α are constants. This is a commonly used attenuation model for wireless transmissions, and it has been verified as applicable to an UWB indoor propagation model [13][14]. Hence, p_{c1} and p_{c2} are functions of d_{12} , d_{21} , d_{11} , and d_{22} . From eqs. (14) and (15), we calculate the two critical distances, d_{c12} and d_{c21} for given values of P_1 , P_2 , d_{11} , d_{22} , and either d_{12} or d_{21} .

$$d_{c21} = \frac{d_{22}}{d_{11}} \cdot \left[\frac{(\rho c d_{12}^{-\alpha} P_1^2 + \eta_2 P_1) \rho c}{\eta_1^2} \right]^{\frac{1}{\alpha}} \quad (17)$$

$$d_{c12} = \frac{d_{11}}{d_{22}} \cdot \left[\frac{(\rho c d_{21}^{-\alpha} P_2^2 + \eta_1 P_2) \rho c}{\eta_2^2} \right]^{\frac{1}{\alpha}} \quad (18)$$

So, if $d_{12} < d_{c12}$ or $d_{21} < d_{c21}$, only one link should be active. This conclusion is equivalent to the concept of "the exclusion regions" in refs. [4--6], but in our case the exclusion regions sizes, d_{c12} and d_{c21} , depend on the transmission powers of the sources, the powers of background noises, the path-loss exponent, and the length of the links; thus our solution is different from the proposition in refs. [4--6].

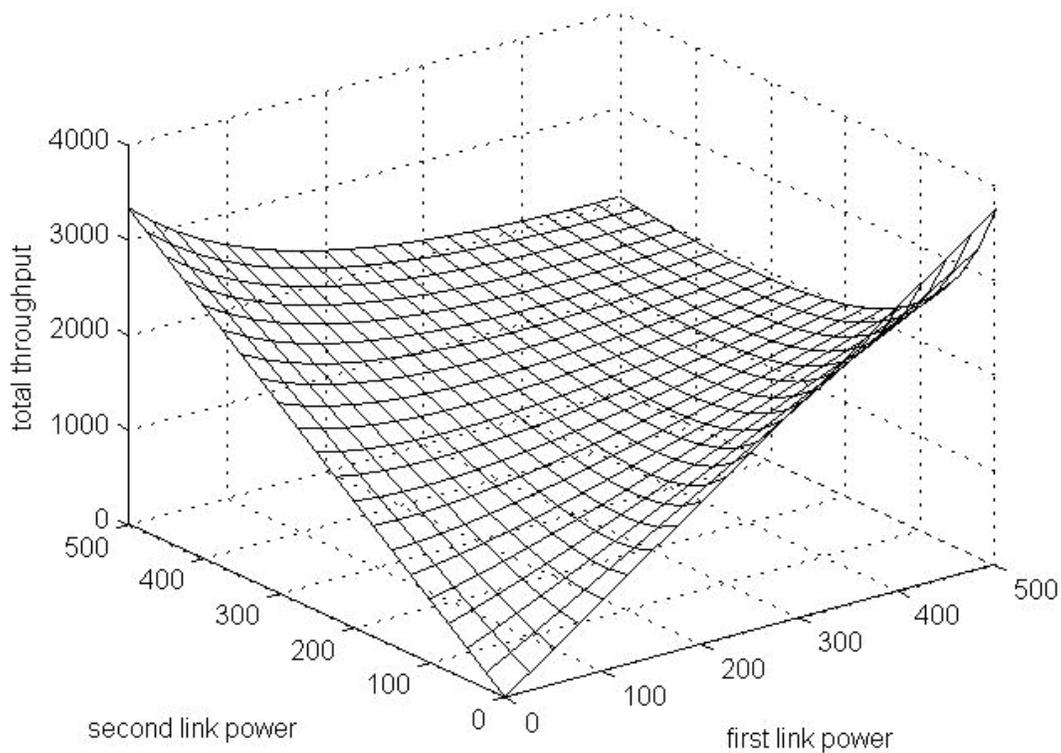


Fig. 4. The maximal total throughput vs. the transmission powers of the two link, when maximum attainable powers are larger than the critical values, for the same parameters' values as in Figure 2 (the total throughput is maximum at $p_1=500$ mW, $p_2=0$ mW)

4. Optimization for N links

We now expand our study to consider the optimization problem of eq. (4) for networks with N active links. Examining the first and second derivatives of (4) with respect to γ_i ($i=1, \dots, N$), we find that all the optimal values of SINRs, γ_i^* ($i=1, \dots, N$), correspond to one and the same value, γ_c , a value which satisfies eq. (9) and (10). So the N optimal rates are

$$R_i^* = \frac{\mu_i}{\gamma_c} = \frac{1}{\gamma_c T_f} \cdot \frac{g_{ii} p_i}{\eta_i + \rho \sum_{k=1, k \neq i}^N g_{ki} p_k} \quad i = 1 \dots N \quad (19)$$

Accordingly, the optimum total network throughput is

$$T^{N*} = \frac{f'(\gamma_c)}{T_f} \sum_{i=1}^N \frac{g_{ii} p_i}{\eta_i + \rho \sum_{k=1, k \neq i}^N g_{ki} p_k} \quad (20)$$

We fix all p_i ($i=1, \dots, N$) at some arbitrary values, except for p_j , and we consider eq. (20) as a function of a single free variable p_j . We can draw curves similar to those in Figure 2, but the values for $p_j=0$ are now the throughputs of the $N-1$ active links. The first and second partial derivatives of (20) with respect to p_j are

$$\frac{\partial T^{N*}}{\partial p_j} = \frac{f'(\gamma_c)}{T_f} \left[\frac{g_{jj}}{\eta_j + \rho \sum_{k=1, k \neq j}^N g_{kj} p_k} - \sum_{i=1, i \neq j}^N \frac{\rho g_{ji} g_{ii} p_i}{\left(\eta_i + \rho \sum_{k=1, k \neq i}^N g_{ki} p_k \right)^2} \right] \quad j=1 \dots N \quad (21)$$

$$\frac{\partial^2 T^{N*}}{\partial p_j^2} = \frac{f'(\gamma_c)}{T_f} \sum_{i=1, i \neq j}^N \frac{2\rho g_{ji}^2 g_{ii} p_i}{\left(\eta_i + \rho \sum_{k=1, k \neq i}^N g_{ki} p_k \right)^3} \quad j=1 \dots N \quad (22)$$

Because eq. (22) is always positive for any $p_j > 0$ ($j=1 \dots N$), T^{N*} is always a concave function, and hence its maximum is only attained either at $p_j=0$ or at the value of maximum transmission power, $p_j=P_j$. Of course, $p_j=0$ means that the link j is inactive, while $p_j=P_j$ means transmission at maximum attainable power. So to solve the maximal throughput problem, we need to determine how many links will be active (transmitting with maximal power). By setting eq. (21) at $p_j=0$ ($j=1 \dots N$) at zero, we can compute a set of critical p_{cj} ($j=1 \dots N$). When $P_j < p_{cj}$ ($j=1 \dots N$), since eq. (21) is always positive, then the maximal total throughput of N active links, T^{N*} , is larger than the maximal throughput of single active link, T^{1*} , and larger than the maximal throughput of $N-1$ active links, $T^{(N-1)*}$. So the optimal scheduling is to allow all the N links to transmit, each at its maximal power. When $P_j > p_{cj}$ ($j=1 \dots N$), the maximal total throughput of N active links might be less than the maximal throughput of a single active link. So, at any particular time, the optimal scheduling should allocate transmission of one active link with large enough power, while the other transmitters are turned off. We could also arrive at this conclusion by the following argument. If we allocate each link's transmitting power as $p_i = a_i p$ ($i=1 \dots N$), a_i being a positive constant or zero, then eq. (20) becomes

$$T^{N*} = \frac{f'(\gamma_c)}{T_f} \sum_{i=1}^N \frac{g_{ii} a_i}{\frac{\eta_i}{p} + \rho \sum_{k=1, k \neq i}^N g_{ki} a_k} \quad (23)$$

We can see that T^{N*} is an increasing function of p . When p is large enough (strictly, infinity), we can obtain

$$T^{N*} = \frac{f'(\gamma_c)}{T_f} \sum_{i=1}^N \frac{g_{ii} a_i}{\rho \sum_{k=1, k \neq i}^N g_{ki} a_k} \quad (24)$$

When more than two links are active, the value of T^{N*} is limited. However, if just one link is active, for example, $a_i=0$ ($i=2 \dots N$) but $a_1 \neq 0$, then T^{N*} tends to infinity.

We consider a special scenario when $g_{ii}=g$, $g_{ij}=g'(i \neq j)$, $\eta_i=\eta$, and $p_i=p$ ($i,j=1 \dots N$). With these conditions, the single active link's maximal throughput is

$$T^{1*} = \frac{f'(\gamma_c) g p}{T_f \eta} \quad (25)$$

However, the maximal total network throughput of N active links is in this case:

$$T^{N*} = \frac{f'(\gamma_c) N g}{T_f \frac{\eta}{p} + (N-1)\rho g'} \quad (26)$$

and each link's maximal throughput is

$$T_1^{N*} = \frac{f'(\gamma_c) g}{T_f \frac{\eta}{p} + (N-1)\rho g'} \quad (27)$$

If we let p go to infinity, T^{1*} will approach infinity as well, but T^{N*} approaches the following finite value:

$$T^{N*} = \frac{N}{N-1} \cdot \frac{f'(\gamma_c)}{T_f} \cdot \frac{g}{\rho g'} \quad (28)$$

We can also see that T^{N*} is an increasing function of N . So with N increasing to infinity, eq. (27) decreases to zero, but eqs. (26) and (28) approach

$$T^{\infty*} = \frac{f'(\gamma_c)}{T_f} \cdot \frac{g}{\rho g'} \quad (29)$$

From comparison, eq. (26) will be smaller than eq. (25) when p is larger than the following value of p_c :

$$p_c = \frac{\eta}{\rho g'} \quad (30)$$

Using eq. (16), we calculate the critical value of the interference distance, d_c' , for transmitted power p :

$$d_c' = \left(\frac{\rho c p}{\eta} \right)^{\frac{1}{\alpha}} \quad (31)$$

In this special symmetric scenario, the critical power, p_c , is independent of N . and the critical interference distance, d_c' , is independent of the link length. When $0 < p < p_c$, the maximal total network throughput is larger than the maximal single active throughput and the increment, $T^{N*} - T^{1*}$, is maximum when p is equal to the following value of p_m :

$$p_m = \frac{\eta}{(\sqrt{N} + 1)\rho g'} \quad (32)$$

When $p=p_m$, eqs. (25) and (26) become, respectively

$$T_m^{1*} = \frac{f'(\gamma_c)}{T_f} \cdot \frac{g}{(\sqrt{N}+1)\rho g'} \quad (33)$$

$$\begin{aligned} T_m^{N*} &= \frac{\sqrt{N}}{\sqrt{N}+1} \cdot \frac{f'(\gamma_c)}{T_f} \cdot \frac{g}{\rho g'} \\ &= \frac{\sqrt{N}}{\sqrt{N}+1} T^{\infty*} \\ &= \sqrt{N} T_m^{1*} \end{aligned} \quad (34)$$

and the maximal throughput of each link is

$$\begin{aligned} T_1^{N*} &= \frac{T_m^{N*}}{N} = \frac{T^{\infty*}}{N + \sqrt{N}} \\ &= \frac{T_m^{1*}}{\sqrt{N}} \end{aligned} \quad (35)$$

Actually, $T^{\infty*}$ is the maximal total network throughput capacity of a network with concurrently active links, and 90% of the maximal total network throughput can be attained when $N=81$. From eq. (29), the maximal total network throughput $T^{\infty*}$ is mainly determined by the physical layer, and it can be enhanced by increasing g (the signal gain) and $f'(\gamma_c)$ (packet transmission success probability increment rate at optimal SINR), and by decreasing T_f (pulse repetition interval), ρ (the shape factor of impulse), and g' (the interference gain). The values of $f'(\gamma_c)$, T_f , and ρ depend on design parameters, such as modulation, pulse shape, time-hopping sequences, and the size of data packets. The values of g and g' depend on the antenna design; e.g., multiple transmit and receive antennas (MIMO) [16] can increase g and decrease g' . However, g and g' are also affected by the routing and the MAC schemes.

5. Discussion and concluding remarks

While the fundamental principles of networking are the same regardless of the underlying physical layer, UWB has unique characteristics that influence how protocols and a UWB system are designed. A UWB network can be represented by a five-layer model, compatible with the TCP/IP suite, that includes a UWB physical layer, associated data link layer, network layer, transport layer, and application layer. Each layer provides services to the layer directly above it and uses services provided by the layer beneath it. The unique characteristics of the UWB physical layer have the greatest influence on the design of the data link layer. The characteristics of the physical layer and the design of the associated data link layer may also influence the design of the network layer, transport layer, and even application layer, especially if a design is to achieve optimal performance.

When designing a communication network, it is important to understand how much information such a network can transport, what parameters affect the maximal throughput of the network, and how to change the parameters so as to maximize the throughput. The two last sections provide us with some answers to these questions for UWB wireless ad hoc

networks. We have established the dependencies among the maximum achievable throughput of the network, each active link's transmission rate and transmission power, the number of simultaneously active links in the network, the link and the interference paths gains, and the background noise.

In the MAC protocol of data link layer, time is divided into time slots, which are allocated for links according to the link-scheduling policy. There are two types of link-scheduling policies: single link policy which allows only one link to transmit in any slot, and concurrent links policy which allows multiple links to transmit simultaneously in a slot. These two policies require that the transmission rate of the active links be maintained at the optimal value according to eq. (19). Under this condition, the maximum total network throughput depends on each link's maximum power and on the interferences among the active links. Our results show that the single link policy suits transmissions with large power: the throughput increases linearly with the power (and, in theory, indefinitely), as shown in eq. (13) and (25). With this policy, the larger is the power, the larger is the throughput. With the concurrent links policy, the maximal total network throughput cannot increase indefinitely by continual increase in transmission powers. Actually, the maximal total network throughput is limited by the interference levels among the active links, and the throughput approaches a finite value when multiple powers are increased indefinitely. This is demonstrated by eqs. (24) and (28). So, on one hand, when the powers are large enough, the single active link maximal throughput exceeds the maximal total network throughput of concurrently active links. In this situation, it is better to choose the single link policy. On the other hand, the maximal total network throughput of the concurrently active links is larger than the maximal throughput of a single active link, if each link power is below the critical value or when the separation between any pair of active links is above their critical values. These critical values are computed in eqs. (14), (15), (30), (17), (18), and (31). Hence, the concurrent links policy is suitable for small powers or for sparse networks. In this situation, each link has an optimum power value which maximizes the throughput gain by increasing the number of the concurrently active links.

The maximal total network throughput with concurrent active links, or the network capacity, is calculated by eq. (29), and can be enhanced by decreasing the interference path gains or by increasing the link path gain, but not by increasing the power. As the number of concurrently active links, N , is increasing, each link throughput is decreased. Existing protocols (like 802.11) are based on the single link policy, but their rate might not be optimum. The regulatory bodies (like FCC) impose severe limitation on UWB power density to avoid interference on other existing wireless communication systems (such as GPS and 802.11 networks), since they share the same frequency band. The FCC regulation allows commercial UWB devices to emit no more than -41 dBm/MHz of average transmitted power, so the maximum transmitted power is limited to less than -2.2 dBm, or approximately half a Milliwatt. Consequently, the concurrent links policy may be a more suitable choice for UWB ad hoc networks.

Because the routing protocol of network layer determines the paths of data flow and interference gains between intended links, the design of an MAC protocol based on the concurrent links policy should be related to the choice of a routing protocol for maximization of the total network throughput. However, the design of an MAC protocol based on the single link policy should be independent of the choice of routing protocol. As the rate adaptation requires support of the physical layer, such adaptation is most efficiently

performed if the design is based on cross-layer considerations. The application of our results to implementation of an MAC protocol based on the concurrent links policy with cross-layer design considerations is outside the scope of this chapter, but is left for future study.

When a mechanism for adaptation of transmission rates is incorporated into the design of the MAC protocol, by adjusting the transmission rates to their optimum values, the maximal total network throughput is limited by maximal transmission power and by the interference from other active links in the networks. The maximal total network throughput approaches a constant and each link's throughput approaches zero as the maximal transmission power and the simultaneously active links increase in number. For the case of a single active link, the maximal throughput increases linearly with the maximal transmission power and, barring a limit on transmission power, the maximal throughput can increase indefinitely. When the values of the maximal transmission power are large enough, the maximal throughput in the single active link case exceeds the maximal total network throughput of the multiple active links case. To maximize the total network throughput, the optimal transmission scheduling should allocate at any time transmission on one link only when the maximal transmission power is large and the interference is strong. However, when the maximal transmission power is small and the interference is weak, the optimal transmission scheduling should allocate at any time simultaneous transmission on multiple links.

6. Summary

In this chapter, we study the problem of radio resource allocation, both transmission rates and transmission powers, so as to maximize the throughput of UWB wireless ad-hoc networks. Our analysis is based on the packet-success function (PSF), which is defined as the probability of a data packet being successfully received as a function of the receiver's signal-to-interference-and-noise-ratio (SINR). We find an optimal link transmission rate, which maximizes the link's throughput and is dependent on the all active links transmission powers. If each link transmission rate is adapted to this optimal link transmission rate, then, with single-link operation (i.e., no other interference sources are present), the link's throughput is directly proportional to the transmitter's power and increases indefinitely with increasing transmission power. However, with multiple-links operation and interference each other, as each link transmitting power increases, so does the interference level, and the total network throughput approaches a constant other than infinite. Thus, for sufficiently small transmission power, the total network throughput of the multiple-links case exceeds the throughput of the single-link case, but the reverse happens for high power. In addition, this chapter reveals that, as the number of concurrently transmitting links increases, regardless of the power level, the maximal total network throughput approaches a constant, with each link's throughput approaching zero. To maximize the network throughput, for the case of small maximal transmission power with weak interference levels, the optimal transmission scheduling allocates simultaneous transmissions of multiple links, but for the case of large maximal transmission power with strong interference levels, the optimal policy assigns separate time for transmission on each link. The breakpoint of when to use one link or multiple links is termed the critical power. As an example of the analytical calculation of the critical link's power, we present here solutions for a two-link case and an N -link case. In contrast with previous studies, our results imply that the design of optimal MAC is dependent on the choice of a routing scheme.

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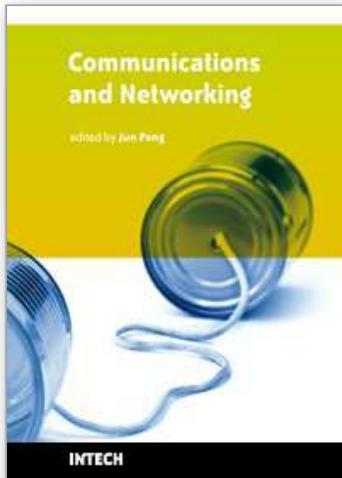
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