SCIENCE CHINA
Information Sciences

• RESEARCH PAPERS •

December 2010 Vol. 53 No. 12: 2538–2547
doi: 10.1007/s11432-010-4120-8

Throughput maximization in UWB-based ad-hoc networks

ZOU ChuanYun[1]*, HAAS Zygmunt J.[2] & ZOU Sheng[3]

[1]*School of Information Engineering, Southwest University of Science and Technology, Mianyang* 621010*, China;*
[2]*School of Electrical and Computer Engineering, Cornell University, Ithaca, NY* 14853*, USA;*
[3]*School of Information of Science and Technology, University of Science and Technology of China, Hefei* 230026*, China*

Received March 27, 2009; accepted October 30, 2009

Abstract In this paper, 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 paper 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.

Keywords UWB, impulse radio, ad-hoc networks, throughput, rate, power, resource allocation

Citation Zou C Y, Haas Z J, Zou S. Throughput maximization in UWB-based ad-hoc networks. Sci China Inf Sci, 2010, 53: 2538–2547, doi: 10.1007/s11432-010-4120-8

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

---

*Corresponding author (email: zoucy@swust.edu.cn) 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. The United States Federal Communications Commission (FCC) has issued a First Report and Order regulating the use of UWB devices, effectively restricting them to the band between 3.1 and 10.6 GHz. Communication over UWB is particularly attractive due to its high 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 [1–8]. 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 or mobile ad-hoc networks (MANETs) are the main uses considered. MANETs do not require any infrastructure, a feature which allows for instant deployment and rerouting of traffic around failed or congested nodes. Since in MANETs it is unnecessary to deploy base stations, the cost of a MANET 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 [9]) of this type of networks is also significantly improved. MANETS can be reconfigured to adapt its operation in diverse network environments. As the results of these characteristics, MANETS became of interest to the commercial and to the military markets. Applications include battlefield deployments, where the transceivers can be mounted on unmanned aerial vehicles (UAVs), on moving armored vehicles, or even carried by individual soldiers. Examples of other applications that were considered are for communication during disaster relief efforts, communications for firefighters, or for law enforcement officers when operating in a hostile environment. Finally, MANET could also be used to set up networks among students in classrooms or among delegates at a convention center.

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 i) 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]; ii) the optimal size of the exclusion region depends only on the path-loss exponent, the background noise level, and the cross-correlations factor [6]; iii) each node should either transmit with full power or not transmit at all [7]; iv) the design of MAC is independent of the choice of a routing scheme [5].

In this paper, we analyze and investigate the maximal total network throughput of UWB based ad-hoc wireless networks. The objectives of our work are (i) 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 (ii) to determine the implications of these dependencies on the allocation and scheduling of the network resources.

The paper 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 we include some concluding remarks.

2 Analytical model

We consider an ad-hoc wireless network 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 layer based on some traffic requirements.

We assume that the physical link layer is based on the Time Hopping with Pulse Position Modulation (TH-PPM) scheme, described in [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 LPPM-modulated pulses. An analytic TH-PPM representation of the transmitted signal of the kth node is given by

$$s^k(t) = \sum_j w(t - jT_f - c_j^k T_c - \delta D^k_{\lfloor j/L \rfloor}), \tag{1}$$

where $w(t)$ denotes the monocycle pulse waveform, T_f is the nominal frame or pulse repetition interval, c_j^k 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 kth 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 paper 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 ith link's receiver is represented as γ_i and is defined as (see [10]),

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

where R_i is the data transmission rate of ith link and $R_i = 1/(LT_f)$, p_i is the average transmission power of the ith link's transmitter, g_{ij} denotes path gain from the ith link's transmitter to jth link's receiver (g_{ii} is referred to as the ith 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 ith link's receiver, and ρ represents a parameter which depends on the shape of impulse (see (79) in [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 ith link as the number of packets per second received without error at the ith link's receiver:

$$T_i^N = R_i f(\gamma_i), \tag{3}$$

where $f(\gamma_i)$ is the packet success rate, i.e., it is the probability that the ith 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 $0 \leqslant f(\gamma_i) \leqslant 1$.

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.

$$T^N = \sum_{i=1}^N T_i^N. \tag{4}$$

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:

$$\mu_i = \frac{p_i g_{ii}}{T_f(\eta_i + \rho \sum_{k=1,k\neq i}^N p_k g_{ki})}, \tag{5}$$

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

$$\gamma_i = \frac{\mu_i}{R_i}, \tag{6}$$

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

Given the links' powers p_i ($i = 1, \ldots, N$), 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-link 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

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

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:

$$f(\gamma_c) = \gamma_c f'(\gamma_c), \tag{9}$$

$$f''(\gamma_c) < 0. \tag{10}$$

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

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

With the above conditions, the optimal total network throughput is

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

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 1, 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 Figure 1 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

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

When p_2 is smaller than p_{c2}, T^{2*} 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^{2*}, 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 1, we find that $p_{c1} = 90.\ 95$ mW and $p_{c2} = 155.69$ mW.

In any practical situation, transmission powers are not unlimited. However, 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 $0 < p_1 < P_2$. 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., $[0 < p_1 < P_1, 0 < p_1 < P_2]$. 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 2 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 3 is an example of such a case).

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 ith link's transmitter to jth link's receiver, then

$$g_{ij} = c \cdot d_{ij}^{-\alpha}, \tag{16}$$

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} andp_{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 eitherd_{12} or d_{21}.

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

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

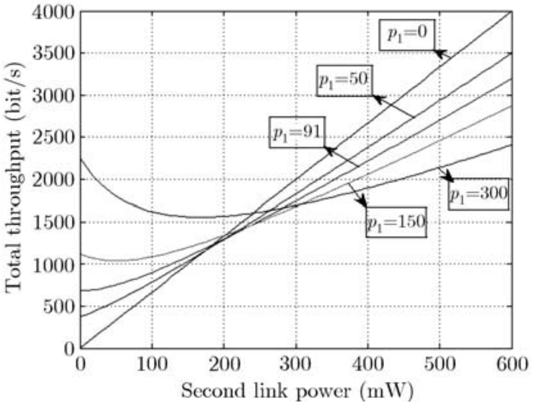

Figure 1 The maximal total throughput vs. the power of the second link, the power of the first link as the parameter, and with the following values of parameters in (12): $f'(\gamma_c)/T_f$= 1 bit/s, g_{11}=0.03, g_{22}= 0.04, g_{21} = 0.003, g_{12} = 0.002, ρ= 0.01, η_1 = 0.004 mW, η_2=0.006 mW, p_{c1}= 90.95 mW, p_{c2}=155.69 mW.

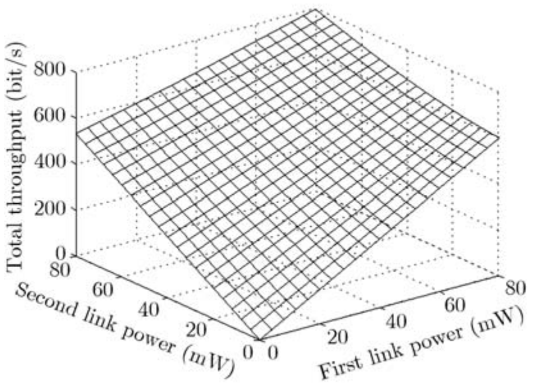

Figure 2 The maximal total throughput vs. the transmission powers of the two links, when maximum attainable powers are smaller than the critical values, for the same parameters' values as in Figure 1 (the total throughput is maximum at p_1=80 mW, p_2=80 mW).

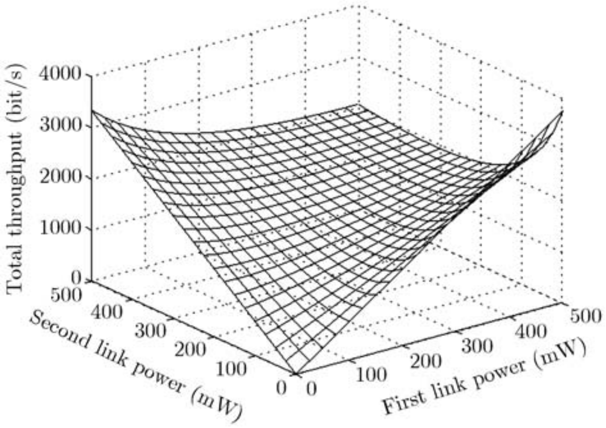

Figure 3 The maximal total throughput vs. the transmission powers of the two links, when maximum attainable powers are larger than the critical values, for the same parameters' values as in Figure 1 (the total throughput is maximum at p_1=500 mW, p_2=0 mW).

Therefore, 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 [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 [4–6].

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 $\gamma_i (i = 1, \ldots, N)$, we find that all the optimal values of SINRs, γ_i^* $(i = 1, \ldots, N)$, correspond to one and the same value, γ_c, a value which satisfies eqs. (9) and (10). Therefore, the N optimal rates are

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

Accordingly, the optimum total network throughput is

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

We fix all p_i $(i = 1, \ldots, N)$ 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 1, 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

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

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

Because eq. (22) is always positive for any $p_j > 0 (j = 1, \ldots, N)$, 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. Therefore, 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 $p_j = 0$ $(j = 1, \ldots, N)$ at zero, we can compute a set of critical p_{cj} $(j = 1, \ldots, N)$. When $P_j < p_{cj}$ $(j = 1, \ldots, N)$, 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, $T^{(N-1)*}$. Therefore, the optimal scheduling is to allow all the N links to transmit, each at its maximal power. When $P_j > p_{cj}$ $(j = 1, \ldots, N)$, the maximal total throughput of N active links might be less than the maximal throughput of a single active link. Therefore, 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 $p_i = a_i p$ $(i = 1, \ldots, N)$, a_i being a positive constant or zero, then eq. (20) becomes

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

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

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

When more than two links are active, the value of T^{N*} is limited. However, if just one link is active, for example, $a_i = 0$ $(i = 2, \ldots, N)$ 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 $p_i = p$ $(i, j = 1, \ldots, N)$. With these conditions, the single active link's maximal throughput is

$$T^{1*} = \frac{f'(\gamma_c)}{T_f} \frac{gp}{\eta}. \tag{25}$$

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

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

and each link's maximal throughput is

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

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

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

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

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

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

$$p_c = \frac{\eta}{\rho g'}. \tag{30}$$

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

$$d'_c = \left(\frac{\rho c p}{\eta}\right)^{\frac{1}{\alpha}}. \tag{31}$$

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:

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

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

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

$$T_m^{N*} = \frac{\sqrt{N}}{\sqrt{N}+1} \cdot \frac{f'(\gamma_c)}{T_f} \cdot \frac{g}{\rho g'} = \frac{\sqrt{N}}{\sqrt{N}+1} T^{\infty *} = \sqrt{N} T_m^{1*}. \tag{34}$$

and the maximal throughput of each link is

$$T_1^{N*} = \frac{T_m^{N*}}{N} = \frac{T^{\infty *}}{N+\sqrt{N}} = \frac{T_m^{1*}}{\sqrt{N}}. \tag{35}$$

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) [15,16] 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

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 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 eqs. (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). Therefore, 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), (17), (18), (30), 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 0.5 mW. Consequently, the concurrent links policy may be a more suitable choice for UWB ad-hoc networks.

Because the routing protocol 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 paper, 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.

Acknowledgements

This work was supported by the Scientific Foundation of Sichuan Education Department of China (Grant No. 2006A096), the Ph.D. Foundation of Southwest University of Science and Technology (Grant No. 06zx7107), and the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Personnel Ministry (Grant No. 08ZD0106).

References

1 Apsel A, Dokania R, Wang X. Ultra-low power radios for ad-hoc networks. In: IEEE International Symposium on Circuits and Systems, Taipei, 2009. 1433–1436

2 Tang X, Hua Y. Capacity of ultra-wideband power-constrained ad hoc networks. IEEE Trans Inf Theory, 2008, 54: 916–920

3 Zou C, Haas Z. Optimal resource allocation for UWB wireless ad hoc networks. In: IEEE 16th International Symposium on Personal, Indoor and Mobile Radio Communications, Berlin, 2005. 452–456

4 Radunovic B, Le Boudec J Y. Optimal power control, scheduling, and routing in UWB networks. IEEE J Sel Area Commun, 2004, 22: 1252–1270

5 Merz R, Le Boudec J Y, Widmer J, et al. A rate-adaptive MAC protocol for low-power ultra-wide band ad-hoc networks. In: Proceeding of 3rd International Conference on AD-HOC Networks and Wireless, Vancouver, 2004. 306–311

6 Liu K H, Cai L, Shen X. Exclusive-region based scheduling algorithms for UWB WPAN. IEEE Trans Wirel Commun, 2008, 7: 933–942

7 Cuomo F, Martello C, Baiocchi A, et al. Radio resource sharing for ad hoc networking with UWB. IEEE J Sel Area Commun, 2002, 20: 1722–1732

8 Baldi P, De Nardis L, Di Benedetto M G. Modeling and optimization of UWB communication networks through a flexible cost function. IEEE J Sel Area Commun, 2002, 20: 1733–1744

9 Tsirigos A, Haas Z J. Analysis of multipath routing——Part I: The effect on the packet delivery ratio. IEEE Trans Wirel Commun, 2004, 3: 138–146

10 Win M, Scholtz R. Ultra-wide bandwidth time-hopping spread spectrum impulse radio for wireless multiple-access communications. IEEE Trans Commun, 2000, 48: 679–691

11 Feng D, Ghauri S, Zhu Q. Application of the MUI model based on packets collision (PC) in UWB ad-hoc network. In: International Conference on Networking, Sensing and Control, Okayama, 2009. 554–558

12 Durisi G, Romano G. On the validity of Gaussian approximation to characterize the multiuser capacity of UWB TH PPM. In: Proceeding of IEEE Conference of Ultra-Wideband Systems Technologies, Baltimore, 2002. 151–161

13 Molisch A F. Ultrawideband propagation channels——theory, measurement, and modeling. IEEE Trans Veh Technol, 2005, 54: 1528–1545

14 Ghassemzadeh S S, Tarokh V. UWB path loss characterization in residential environments. In: Proceeding of IEEE Radio Frequency Integrated Circuits (RFIC) Symposium, Philadelphia, 2003. 501–504

15 Zhu S, Leung K K, Constantinides A G. Distributed cooperative data relaying for diversity in impulse-based UWB ad-hoc networks. IEEE Trans Wirel Commun, 2009, 8: 4037–4047

16 Kaiser T, Zheng F, Dimitrov E. An overview of ultra-wide-band systems with MIMO. Proc IEEE, 2009, 97: 285–312