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Jointly PHY/MAC Capacity for Ultra-wideband Multi-hop Networks

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Abstract: Ultra-wideband (UWB) radio is a fast emerging technology with uniquely attractive features inviting major advances in wireless communications, networking, radar, imaging, and positioning systems. UWB radios offer great flexibility and shows enormous potential in view of future fourth generation (4G) broadband wireless access in dense multipath environments. In this paper jointly PHY and MAC layer lower bound and upper bound throughput capacity of ultra-wideband ad-hoc network has been found under Voronoi tessellation power control using second derivative UWB waveform. These bounds demonstrate that throughput increases with node density (*n*). In the simulation we take into account The FCC UWB and FCC Waiver grant regulations with bandwidth between (3.6–10.1 GHz) at maximum power spectrum density (PSD) -40dBm/MHz. with this large bandwidth, and power and interference control, we depict the significant of jointly (PHY/MAC) properties on capacity of UWB ad-hoc indoor environment networks.

Key words: WPAN, UWB, ad-hoc network, medium access control, wireless network.

INTRODUCTION

Throughput capacity is a key characteristic of wireless networks. It represents the long-term achievable data transmission rate that a network can support. The throughput capacity of a wireless network depends on many aspects of the network: network architecture, power and bandwidth constraints, routing strategy, radio interference, etc.

A random ad hoc network is one in which there are *n* randomly placed nodes with source-destination pairs uniformly and independently chosen. Nodes function as sources, sinks or relays in the transmission of data through the network and are assumed to have infinite buffers to handle relaying. The problems suffered by ad hoc wireless channels are the lack of synchronization and the lack of any predetermined topology, which create many challenging research topics in the area of ad-hoc networks[1]. Traditionally, research has been concentrated on the medium access control, and network[3] layers. Networks with energy constraints are also being studied[4].

Ultra-wideband (UWB) radio is an emerging technique both in the fields of radar applications and digital communications. UWB systems are mostly based on impulse (IR) technology, which has recently reached an appreciable degree of development so as to be able to support high data rates with low power consumption and low complexity in terms of transmission/reception operations[5,6]. By combining a transmission over a wide radio spectrum band with lower power and pulsed data, UWB causes less interference than conventional narrowband radio and offers potential to hit the market in unlicensed bandwidths.

The capacity of random wireless multi-hop networks was studied extensively, In[7], where fixed nodes are randomly placed in the network and each node sends data to a randomly chosen destination. The throughput capacity per node is shown as $\Theta(w/\sqrt{n\log n})$, where *n* is the number of nodes in the network and *w* is the common transmission rate of each node over the wireless channel. Thus the aggregate throughput capacity of all the nodes in the network is $\Theta(\sqrt{n/\log n}W)$. The aggregate throughput capacity of a random three-dimensional wireless ad-hoc network scales as $\Theta((n/\log n)^{2/3}W)$[8].

Due to[7] result, four types of increasing the capacity have been done: (1) uses mobility to increase the capacity[9,10]. Specifically, in a network where nodes move randomly on a unit-area disk such that their steady state distribution is uniform, each source-destination pair can achieve a constant throughput, which is independent of the number of nodes. (2) Hybrid network to increase the

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capacity of wireless networks. In this case, *m* base stations interconnected with wired lines are placed within the ad-hoc network with *n* nodes to help transmit packets successfully.[11] Shows that the number of base stations has to grow at a rate faster than $\sqrt{n}$, in order to effectively improve the throughput capacity. Therefore, the use of infrastructure support requires a large number of base stations interconnected through wired line. (3) Use directional antennas to increase the capacity of wireless networks.[12] Shows that even if the transmitter can generate arbitrarily narrow beams (which essentially removes all wireless interference) and the transmission ranges are set as minimal as possible to maintain connectivity, the capacity can only be improve by an order of $\Theta(\log^2(n))$. Thus the capacity improvement using directional antenna is very limited. (4) Use unlimited spectrum resources, in particular, the Ultra Wideband (UWB)[13]; shows that under the limiting case when the bandwidth *B_ 8* and each node has a power constraint P_0 , the node capacity to increased w.r.t number of nodes. In this paper, we have used UWB as a physical layer where each link operates with relatively large bandwidth and maximum transmission power p_0 for transmission among 100 mobile nodes distributed in unit area desk.

The rest of the paper is organized as follows. Section II presents the UWB fundamentals. Followed by section III, network model; IV presents the simulation results and finally conclusions are given.

UWB Difinition: The Ultra Wide-Band (UWB) radio communications can be viewed as an extreme form of spread spectrum communication systems. UWB radios transmit using very short impulses spread over a very large bandwidth. UWB radios are generally defined to have a fractional bandwidth (*n*) higher than 0.25 (i.e. a 3dB bandwidth which is at least 25% of the centre frequency used).

$$h = \frac{2(f_H - f_l)}{(f_H + f_l)} \tag{1}$$

Where f_H and f_L are high and low frequency respectively. Significant properties for UWB are: low-power consumption, mitigated multi-path fading effects, possibility of high bit rates and unique location ability. Due to the very lower signal levels, which are allowed in the system (< -41dBm), one of the main drawbacks of UWB technology is the high channel acquisition time, i.e. the time to achieve bit synchronization[2].

UWB System model:

Signal model: The transmitted UWB signal consists of a train of short pulses, which dithered by a time-hoping (TH) sequence to facilitate multiple accesses and reduce spectral lines. The polarities of the transmitted pulses also randomised by using a direct sequence (DS) spreading code to mitigate multiple access interference (MAI). The generalized UWB signal transmitted during the acquisition process for a single user can be expressed as a series of 2nd derivatives of Gaussian pulse[3,4].

$$y\,(t) = \sqrt{\frac{4}{3t_n\sqrt{p}}}\left(1-\left(\frac{t}{t_n}\right)^2\right)\exp\left(-\frac{1}{2}\left(\frac{t}{t_n}\right)^2\right) \tag{2}$$

The parameter t_n determines the effective time width of the pulse $T_p$and, hence, it's bandwidth (shown in Figure 1).

$$x(t) = \sum_{l=-\infty}^{\infty} b_{\lfloor l/N_b \rfloor} a_{[l/N_{ds}]} y\,(t - lT_f - c_{[l/N_{th}]} T_c), \tag{3}$$

Where N_b is the number of consecutive pulses modulated by each data symbol b_i , T_f is the pulse repetition period (PRP), T_c is the chip duration, which is the unit of additional time shift provided by the TH sequence and $[.]$, $\lfloor . \rfloor$ denote the integer division reminder operation and the floor operation, respectively. The pseudorandom TH sequence $\{c_l\}_{l=0}^{N_{th}-1}$ has length N_{th} where each takes integer values between 0 and , $N_{th} - 1$ where N_{th} is less than the number of chips per frame $N_f = T_f / T_c$. The DS sequence $\{a_l\}_{l=0}^{N_{ds}-1}$ has length N_{ds} with each a_l taking the value +1 or –1.

Channel model: The UWB indoor propagation channel can be modelled by a stochastic tapped delay line[5], which can generally be expressed in terms of its impulse response

$$h(t) = \sum_{k=0}^{N_{tap}-1} h_k f_k (t - t_k), \tag{4}$$

Where N_{tap} is the number of taps in the channel response, h_k is the path gain at excess delay t_k corresponding to the k-th path. Due to the frequency sensitivity of the UWB channel, the pulse shapes received at different excess delays are path-dependent[9]. The function $f_k(t)$ models the combined effects of transmitting and receiving antennas and propagation channel corresponding to the k-th path of the transmitted pulse. The received signal from a single user can then expressed as

$$r(t) = \sum_{l=-\infty}^{\infty} b_{\lfloor l/N_b \rfloor} a_{[l/N_{ds}]} w_r (t - lT_f - c_{[l/N_{th}]} T_c - t\,) + n(t), \tag{5}$$

where

$$w_r(t) = \sum_{k=0}^{N_{tap}-1} h_k y_{\,k}(t - t_k), \tag{6}$$

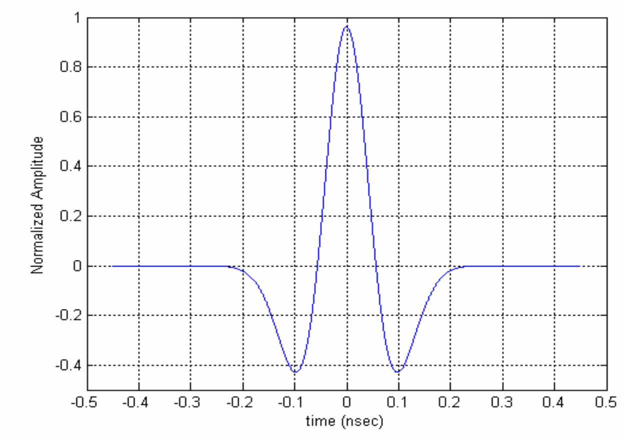

Fig. 1: second derivative of Gaussian pulse Then the transmitted signal is given by

is the received waveform corresponding to a single pulse. Here $R_k(t)=f_k(t) * R(t)$ is the received UWB pulse from the k-th path. The duration of the received pulse T_w is assumed to be less than the chip duration T_c. The propagation delay is denoted by J and n(*t*) is a zero mean noise process. Given the received signal, the acquisition system attempts to retrieve the timing offset J.

Network model:

A Voronoi tessellation (V_n): The Voronoi cell V(a_i), (i=a,b,...p), is the set of all points which are closer to a_i than to any of the other a_j's, i.e.,

$$V(a_i) = \left\{x \in S^2 : \left|x - a_i\right| = \min_{1\le j\le p}\left|x - a_j\right|\right\} \qquad (7)$$

Throughput capacity and distances are measured on the surface S^2 of the sphere by segments of great circles connecting two points[5]. The point a_i is called the generator of the Voronoi cell V(a_i). Figure 2 shows an example of a tessellation of S^2.

For the Voronoi tessellation can be defined:

1) Every Voronoi cell V contains a disk of area (100 log *n*)/*n* and *D*(*n*) is the radius of the disk.
2) Every Voronoi cell V is fully contained within a circle of radius 2*D*(*n*), and each cell should contains at least one node.
3) The range of each transmission *r*(*n*)=8*D*(*n*) allows direct communication within cell and between adjacent cells as shown in Figure 3.
4) Every two cell are interfering neighbours if there is a point in one cell which is within a distance (2+))*r*(*n*) of some point in the other cell; and every cell in V_n has no more than (c_1) interfering neighbours, where (c_1) is the ratio of the maximum interference area and the minimum area of each cell. It is depends only on) and grows no faster than linearly in $(1+))^2$.
5) For the protocol and physical model the transmission schedule for packets such that in every (1+c_1) slots, each cell get one slot, and all transmissions are successfully received within distance *r*(*n*) from transmitter under certain conditions, the available capacity for each cells depends on c_1 and length of frame T.

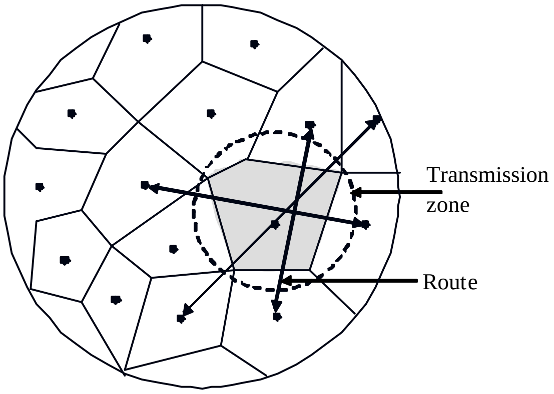

Fig. 2: A Voronoi tessellation of the surface S2 of the sphere.

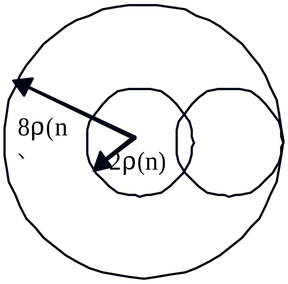

Fig. 3: The parameters of the cell in the.

$$\text{Available capacity} = T/(1+c_1) \text{ pbs} \qquad (8)$$

and the rate for each cell for transmit is $W/(1+c_1)$ bps

6) To choose the routes of packets to approximate the straight line segments. The straight-line segment L_i will intersect many cells in the tessellation V_n. Let V_i denote the particular cell, which contains X_i and Vt_i the cell, which contains Y_i. Packets originating at X_i will be relayed from the cell V_i to the cell Vt_i in a sequence of hops. In each hop, the packet is transferred from one cell to another in the order which they intersect the line. (If two cells are both "next" cells, then either can be chosen arbitrarily). Finally, after reaching the cell Vt_i containing Y_i, the packets will be sent on their final destination.

MAC Layer: The interference problem in the ad-hoc network is first addressed. It is shown that the interference perceived by a receiver is bounded w.h.p, and hence, a certain scaling of bandwidth W, as a function of n, renders the interference negligible. This implies that under the limiting bandwidth assumption, a 'CDMA MAC scheme' is optimal. i.e., all transmitters transmit at the same time, using the entire bandwidth. Here 'optimal' is used in comparison to time/frequency scheduling schemes as noted subsequently.

Power Control: The power control is the procedure of determining the transmitted power of each communication terminal in the ad-hoc network. Adjusting the transmitted power is extremely important in ad-hoc networks due to at least the following three reasons:

- The transmitted power of the radio terminals determines the network topology. The network topology in turn has considerable impact on the throughput performance of the network.
- The communication terminals in the ad-hoc networks are usually energy constraint; hence they have to be as energy efficient as possible. So the power control should adjust the transmitted power to be the least power required to send the data packet at the target QoS.
- Transmitting at high power can degrade other communication systems and networks. This is especially for the terminals use UWB as a radio interface.

To determine the appropriate transmitted power value the transmitting node needs to know at least the Signal to Interference and Noise Ratio (SINR) at receiving node. If the SINR is lower than target value then the transmitting node increases its transmitted power. And if the SINR is larger than some target value then the transmitting node reduces its transmitted power to save energy as well as improve the total system performance. The SINR is estimated at the receiving node and then sent back to the transmitting node in feedback channel. If there is large delay in the feedback channel so that the channel conditions are changed then the transmitting node will adjust the power to wrong value. This could degrade the performance of the ad-hoc communication system. If wideband feedback channel is used then the transmitted power of node *i* can be calculated as

$$P_i(t+1) = \frac{d_{ij}^{T}(t)}{d_{ij}(t)} P_i(t) \qquad (9)$$

Where $P_i(t)$ is the transmitted power of node *i* at iteration t, $*_{ij}^{T}$ is the target SINR to send data from node *i* to node *j* at iteration t, and $*_{ij}(t)$ is the actual SINR of node *i* at the receiver *j* at iteration t. Note that the target SINR can change from slot to slot, it depends on the data rate and the target BER for a given packet. The SINR formula depends on the modulation technique. In CDMA the SINR can be represented as

$$d_{ij}(t) = PG_i(t)\frac{P_i(t)G_{ij}(t)}{\sum\limits_{\substack{k=1\\ k\neq i\\ k\neq j}}^{Q} P_k G_{kj}(t) + N_j}, \quad t = 1,2.. \qquad (10)$$

Where $PG_i(t)$ is the processing gain, N_j is the additive white noise at the receiving node. $G_{ij}(t)$. Is the channel gain between nodes node *i* to node *j*, this is modelled as a combination path loss (") and Rayleigh fading (multipath) channel (r_{ij}) where

$$G_{ij}(t) = \frac{1}{\left|x_i - x_j\right|^{a}} \quad r_{ij} \qquad (11)$$

The signal to interference noise ratio (SINR) also can be written as follows:

$$SNR = \frac{P}{N_s s_a^{2}(N_u - 1) + s_{rec}^{2}} = \frac{(N_s m_p)^2}{N_s s_a^{2}(N_u - 1) + s_{rec}^{2}} \qquad (12)$$

Where P is the average power of the useful signal, s_{rec}^{2} is the power of the thermal noise, F_a^2 is the power of the interference resulting from one user, and m_p is the signal at the correlator's output during the interval T_f. Equation (12) shows that global system performance depends on the amount of multi-user interference, which in turn is determined by the correlation properties of the time-hopping codes. Most often, pseudo-random codes are used, due to their good cross-correlation properties.

Routing: In the case of UWB network, the severe power limitations due to coexistence requirements lead to the conclusion that the key system parameter is emitted power, which affects the multi-user interference (MUI) in the intra-piconet routing (direct connection link when the radios of piconets $\leq$ 10m). In inter-piconet a metric based on distance between nodes will be adopted to select the relaying node when no direct connectivity between source and destination is available.

The cost of the link when taking into account the above aspects defined as:

$$\mathrm{C(power)} = \mathrm{C_1.R(x,y).d^{a}(x,y)} \qquad (13)$$

Where R is the requested rate on the link, d is the distance between two nodes, " propagation constant, and C_1 a constant used to weight the signalling and transmission component. Beside power we can consider interference, quality set-up, and delay in the link to calculate the total link cost. The distance between any two nodes can be obtained by using UWB precise location capability; this will be the subject of future investigation.

RESULTS AND DISCUSSIONS

Computer simulations were used to investigate throughput capacity for 100 mobile nodes in random wireless multi-hop network (all parameters were shown in Table I), which results shows that the throughput capacity increased with increasing number of nodes, which it decreased when other techniques like IEEE802.11 (a/g) used. The unique feature of UWB with infinity bandwidth (three types of UWB were used . 3.1 GHz for TH-SS UWB, 2G Hz and 4.744 GHz for DS-CDMA UWB system, and 528 MHz for MB-UWB system that proposed to IEEE802.15.4 study group), very low power ?10ìw, which provides increasing in the capacity with propagation delay " ≥ 1.

Results shows that UWB SNR below the noise floor for other systems[3], which means no harmful interference to those systems that UWB overlaid their frequencies (i.e. Wi-Fi or IEEE802.11).

Bandwidth Scaling: A certain bandwidth scaling can render the interference negligible with respect to ambient noise (N_0). Nodes arbitrarily close to the receiver cause arbitrarily large interference, which occur in the case of unit area network model, Figure 4 shows that in the microcell, SIR will increase with increasing number of UWB nodes.

Figure 5 show the probability of nodes is closer to receiver node, which we consider two scenarios: unit area case, which the area of the network has been normalized to unity. Thus, the node density increases linearly with n. area scaling where the area A increases with n, as nA_o.

UWB Signal to Interference and Noise Ratio: By consider the set of all nodes interfering (the set of all simultaneous transmitters), UWB shows a very low interference to its network environments and to other wireless systems devices. This is shown in Figure 6.

Throughput Bound: The final throughput capacity for ultra-wideband ad-hoc networks shown in Figure 7, for UWB single band (UWB-SB) using TH-SS UWB and 2PPM modulation scheme with time duration T_m=0.9 nsec and bandwidth 2.1GHz, and very low power (?10ìw), which provides increasing in the overall network capacity with

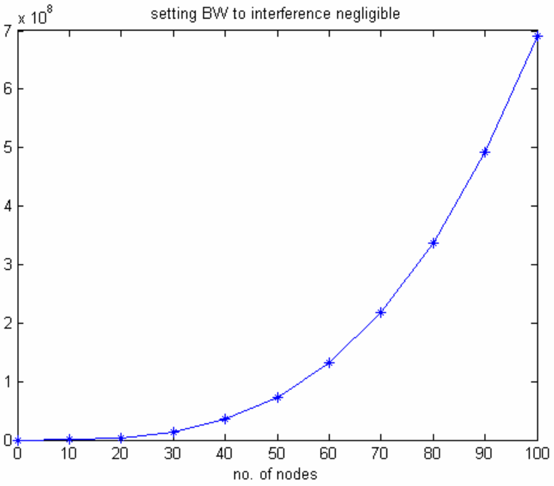

Fig. 4: Setting bandwidth to negligible interference

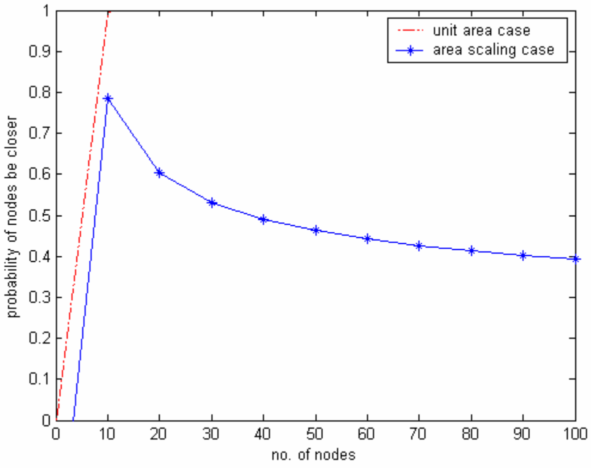

Fig. 5: Probability of nodes is closer to receiver node, for area scaling and unit area case.

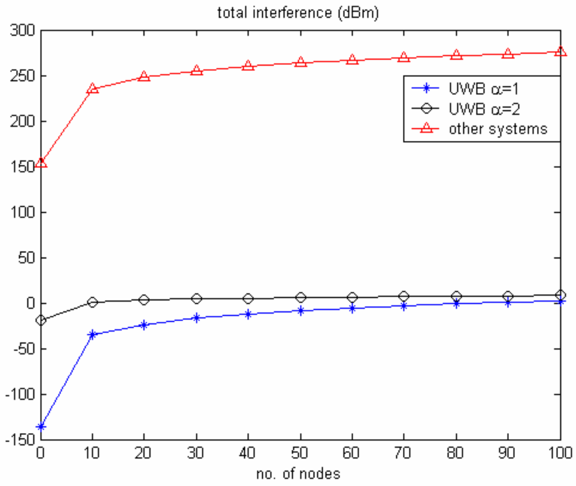

Fig. 6: UWB total interference to other devices compared to other systems interference

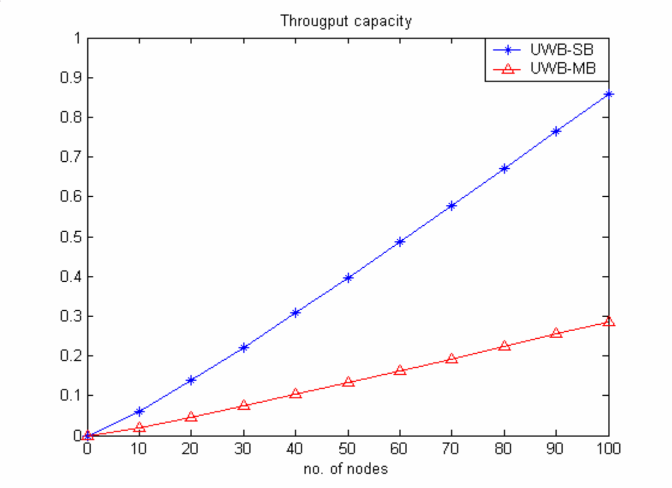

Fig. 7: UWB (Single Band, Multi-Band) throughput capacity

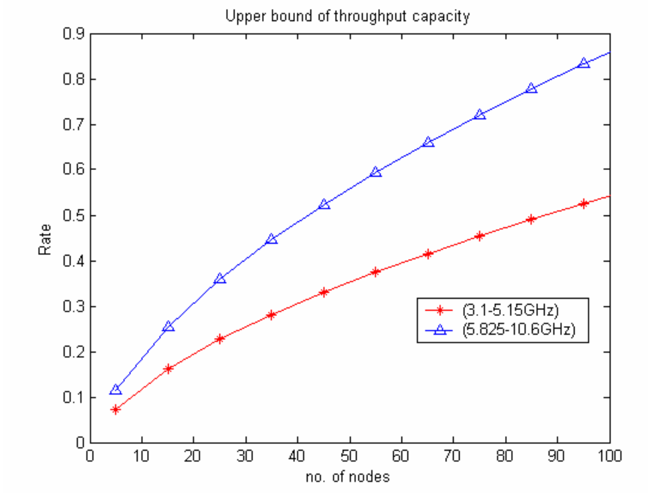

Fig. 8: Bound throughput capacity for UWB ad-hoc network

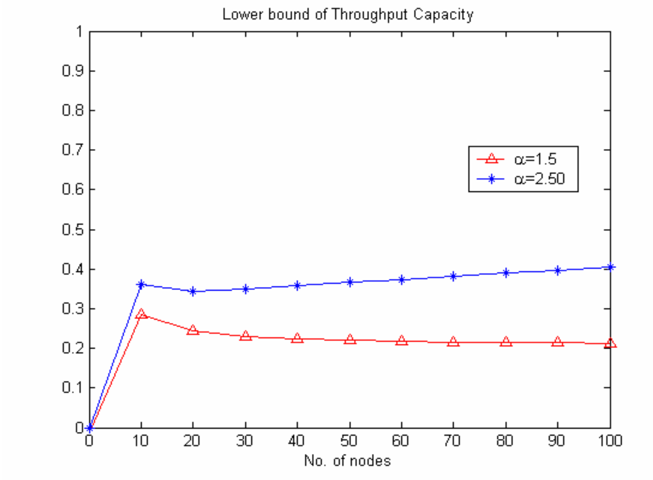

Fig. 9: Lower bound throughput capacity for various propagation exponents constant

Table 1: Simulation parameters

n	100
nodesArea size	10x10 m^2
P_{max}	10μW
SINR	0dB
N_0	0.5+e^{-6} mW
$*^2$ (Rayleigh)	2
T_f (Frame Time)	100ns
T_c (length of chips)	0.7ns
Signal duty cycle (SDC)	10^{-3}
N_c (no. of chips)	7ns

propagation delay " ≥ 1.

UWB multiband (MB-UWB) with symbol duration of 312.5 nsec and a bandwidth of 528 MHz. Because of large bandwidth UWB-MB give throughput capacity smaller than UWB-SB, but it gives robust interference mitigation in ad-hoc network environment, and for other co-existent systems, also give good QoS with multimedia applications. These results show the evaluation of the capacity comparison with the throughput capacity for ad-hoc network by using IEEE802.11b.

Figure 8, shows the upper throughput capacity for the two bandwidths of DS-CDMA UWB (3.1-5.15 GHz & 5.825-10.6 GHz) proposed to IEEE 802.15.4 study group. Figure 9, shows the lower throughput capacity for two values of propagation exponent constant (").

Conclusions: This paper shows the capacity of multi-hop ad-hoc network under low power UWB via computer simulation and analysis with arbitrary large bandwidth. In particular, it studies UWB PHY interactions with ad-hoc network, their effect on network capacity, and the scaling behaviour of throughput capacity as the network grows. The throughput capacity bounds for ad-hoc network using UWB (i.e., W6*BW* 6 4 and each node has a power constraintP_o) demonstrates an increasing per-node throughput assumption increased as number of nodes increased. Thus, the properties of PHY/MAC UWB cross-layer dramatically alter the ad-hoc network capacity bounds.

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