Link Protocol Based on DS-CDMA with MUD for Decentralized All-Connected Wireless Network

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Abstract. To fulfill the application of wireless network in small area, this paper proposed a protocol for decentralized all-connected wireless network. This protocol is based on DS-CDMA with the ability of multi-user detection (MUD). And it has the characteristics of transmitting data in parallel, high network throughput and low communication error rate. In this paper, the process of the protocol is introduced, and an improved quasi-synchronous decorrelation multi-user detection algorithm is deduced in detail. And then, the protocol is simulated and the results are analyzed.

Keywords: Decentralized network, multi-user detection, DS-CDMA.

1 Introduction

Compared with centralized wireless network, decentralized wireless network architecture is more suitable to be used in this environment[9]. That is because decentralized network needs no station, nodes are more autonomous and the network is more robust[4]. And wireless link could be assumed as physically connected when nodes are within a short distance one another. Therefore, the network described above can be simplified as decentralized all-connected model[3]. This paper will propose a protocol to be used in this environment to accomplish a no delay, low power cost, high anti-interference wireless network.

Among common link protocols, such as ALOHA, Carrier Sense Medium Access (CSMA), Multiple Access With Collision Avoidance (MACA), Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA)[4], CDMA system has the characteristics of strong anti-interference ability and good security[1]. Especially, the theory of Direct Sequence CDMA (DS-CDMA) system is simple, its power cost is low, and it is easy to be realized[1], so it is very suitable to be used in local quickly deployed temporary wireless network. However, in practical system, when using DS-CDMA strategy to realize multiplexing, the spreading codes used by transceivers could not be exactly in quadrature, which will lead to nonzero cross correlation. This cross correlation will produce multi address interference (MAI), and finally forms a near-far problem[6]. As in decentralized network, power control can be hardly realized[7], while MUD technique not only can eliminate or decrease MAI, but also its performance is far better than power control [8]. Therefore, MUD is a necessary technique to improve the performance of DS-CDMA network system.

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By analyzing the MUD DS-CDMA system, this paper designs a network protocol based on MUD DS-CDMA architecture. And then, a quasi-synchronous decorrelation MUD algorithm is promoted in this paper, according to the practical network characteristics. Finally, the protocol is simulated and its performance is analyzed.

2 The Process of the Accessing Protocol

2.1 Protocol Initialization

In the spread spectrum communication system, the transmitter spreads the signal spectrum by a spreading code that is independent of the signal. The receiver could only receive useful information by using the same spreading code as the transmitter to despread the signal, or else, the signal from the transmitter would be treated as noise. Meanwhile, in the all-connected network, link could be established between any two nodes, and then they can do operations like accessing and transmitting[9]. Considering the system characteristics listed above as well as the application requirements described in section one, the initial protocol is designed as follows:

a. Allocate two spreading codes, which are defined as transmitting code (TC) and receiving code (RC), for each known node. And each node in the network knows other nodes' spreading code information. In idle state, each node uses its own RC to dispread signal, preparing to receive data. The dispreading code of each node is approximately in quadrature to make sure the independence of the channels in the communication process, so that multi-node-pairs can implement the protocol on the same spectrum at the same time.

b. All the nodes in the network communicate each other by using the allocated spreading codes to make sure that the channels are independent. Therefore each node can use its spreading code as its address code to accomplish the addressing operation without any other control orders.

c. The source and dest nodes check the occupation of the channel by specific handoff operations, during which the spreading code (addressing code) is exchanged between them. During the data transmission period, the source and dest nodes use specific information interaction and retransmission mechanism to check and protect the integrity of the received data, which is implemented according to the HDLC protocol[14]. After transmission, still use handoff operation to release the occupied spreading code and the channels are also released.

Based on the settings above, the operation flow of the link layer protocol is as follows:

2.2 Establishing Link Process

When node 1 wants to communicate with node2, it first changes its RC to TC2 to make sure that it does not response to other node's request, and listens in node 2 to judge whether it is transmitting or not. If not, node 1 uses RC2 to transmit its RTS (Request to Send) packet. As the spreading codes are in quadrature, only node 2 could receive this request. On receiving the RTS packet from node 1, node 2 changes its RC to TC1, preparing to receive data from node 1. Then, node 2 will use TC2 to reply CTS (Clear to Send) packet and transmit data to node 1. When node 1 receives CTS, it will use TC1 to transmit data.

When node 1 needs to send data to node 2, but node 2 is using TC2 to communicate with node 3, node 1 will receive the data from node 2, so it will not send RTS to node 2 in this case. Then, node 1 will set a timer and listen in node 2 until its transmission is over or the timer is expired. When the transmission of node 2 is finished, node 1 will send RTS to node 2 immediately and communicate with node 2. When the timer expires, node 1 will retreat for a while, and try again as the rule described above until the link is established. The process is shown in figure1.

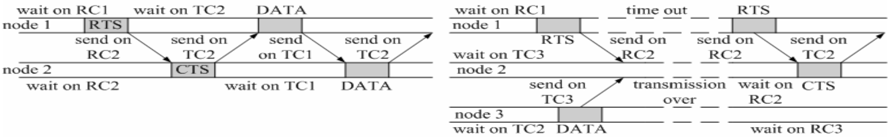

Fig. 1. The link establishment when dest node is idle (left) or under transmitting (right)

By the link establishment process described above, the hide and exposed terminal problems in wireless network could be solved[6]. By using the technique of channel listening, the idle waiting time in link establishment will be decreased. And the nodes use their own spreading code to connect, so multi nodes could establish links at the same time, which will increase the throughput of the network greatly.

2.3 Data Transmission Process

To improve the data validity and decrease the retransmission overhead of the network, sequence detection of data frames and partial retransmission mechanism are adopted in this paper. When the link between node 1 and node 2 is established, node 1 will send data to node 2 frame by frame in order. Node 2 will open a window to store a certain amount of received frames and check the serial number of the frame. When node 2 discovers that the frame with the expecting number is lost, it will request node 1 to retransmit the frame with the specific number. In another case, node 1 sends frames with request response (RR) information. When node 2 receives these frames, it will response the frame with its number in the response frame (RES). By doing this, node 1 could judge whether some frames are lost or node 2 is still active[14]. The transmission process is shown in figure 2, in which the window size is 3.

The design of the transmission process makes sure both the correction of transmission error and the data validity of transmission. Meanwhile, nodes in the

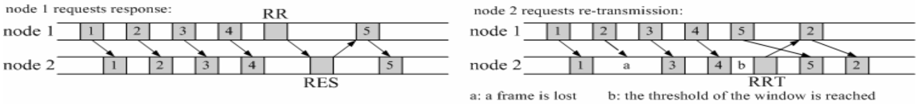

Fig. 2. Transmission process with sequence detection

network exchange control demands only when data validity is needed. By doing this, the overhead of control demands is decreased, and transmission efficiency is improved. What's more, this transmission protocol sets window length according to the channel quality, so the balance between checking rate and processing time is guaranteed.

2.4 Disconnection Process

After transmission, node pairs need a handshake to return to idle state, in order to release the occupied code division channel by releasing the communication spreading code. In normal state, if the link is started by node 1, node 1 will send disconnecting request (DIS) to node 2 after the transmission. Node 2 will send the disconnecting response (DISR) to node 1. Then node 1 and node 2 switch their receiving codes to RC1 and RC2 respectively to prepare for a new transmission. During the following two conditions, the link will be forced to disconnect. First, node 1 does not receive any data from node 2 although it sends disconnecting request for many times, it will disconnect unconditionally. Second, in the transmission process, if one node does not respond for a long time, the other one should be forced to disconnect. The disconnecting process is shown in figure 3.

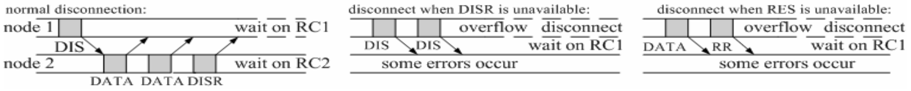

Fig. 3. Normal disconnection and forced disconnection processes

The design described above takes accessing interference, throughput, transmission validity, control command overhead and error operation time in to consideration. The final goal is to improve the performance of the whole network. The detail analysis of each factor listed above will be given in the fourth section. Before this, let's go back to focus on the quality of the physical communication channel based on DS-CDMA network in the next section.

3 Design of Ulti-user Detection Strategy

3.1 Introduction of Asynchronism DS-CDMA MUD

The code division isolation of channels ensures the ability of parallel transmission among transceivers and MAI is much stronger than other interferences arisen by channel when multi transceiver-pairs transmit data at the same time. Therefore, the proposed protocol in section two must take MAI into consideration, or else, the SNR (Signal Noise Rate) will be decreased if MAI is treated as noise interference, which will influent the transmission ability[10]. However, the influence will be eliminated or decreased if MUD technology is adopted to extract useful information from MAI.

Next, the asynchronism DS-CDMA de-correlation MUD model will be derivate in detail. Based on this derivation, a MUD algorism suited for decentralized all-connected wireless network is proposed.

In the all-connected network described in the second section, the received signals from multi transmitters are asynchronous. Therefore, asynchronous DS-CDMA model is adopted to describe signals at receivers in the network[11]. Assumed that there are K nodes in the network and the information length of node k is $N=2M+1$. Then base band spreading signal of node k is:

$$s_k(t)=\sum_{i=-M}^{M}\sqrt{2E_k}\,b_k(i)\,c_k(t-iT) \tag{1}$$

In which $b_k(i)$ is the i th information bit sent by node k, and $b_k(i)\in\{-1,1\}$, $k=1,2,\cdots,K,\ \ i=-M,\cdots,M$, E_k is the receiving power of node k, T is the bit width of spreading code. So the base band signal of the receiver is:

$$r(t)=\sum_{k=1}^{K}s_k(t-\tau_k)+n(t)=\sum_{i=-M}^{M}\sum_{k=1}^{K}\sqrt{2E_k}\,b_k(i)\,c_k(t-iT-\tau_k)+n(t) \tag{2}$$

in which τ_k is the transmission delay of node k, and $\tau_1\le\tau_2\le\cdots\le\tau_K$.

Assumed that the receiver uses matched filter for correlation dispreading, then for receiving signal, the ith bit of the client k of the matched filter's output is:

$$\begin{aligned}y_k(i)&=\int_{iT+\tau_k}^{(i+1)T+\tau_k}r_i(t)\,c_k(t-iT-\tau_k)\,dt=\int_{iT+\tau_k}^{(i+1)T+\tau_k}\sum_{j=1}^{K}\sqrt{2E_j}\,b_j(i)\,c_j(t-iT-\tau_j)\cdot c_k(t-iT-\tau_k)\,dt\\&=\frac{1}{T}\int_{iT+\tau_k}^{(i+1)T}\sum_{j=1}^{K}\sqrt{2E_j}\,b_j(i)\,c_j(t-iT-\tau_j)\cdot c_k(t-iT-\tau_k)\,dt+\\&\quad\frac{1}{T}\int_{(i+1)T}^{(i+1)T+\tau_k}\sum_{j=1}^{K}\sqrt{2E_j}\,b_j(i)\,c_j(t-iT-\tau_j)\cdot c_k(t-iT-\tau_k)\,dt+n_k(i)\end{aligned} \tag{3}$$

$$\begin{aligned}&=\sqrt{2E_k}\,b_k(i)+\Big\{\sum_{j<k}\sqrt{2E_j}\,b_j(i+1)\,\rho_{kj}(\tau_j-\tau_k)+\sum_{j<k}\sqrt{2E_j}\,b_j(i)\,\rho_{jk}(\tau_k-\tau_j)\\&\quad+\sum_{j>k}\sqrt{2E_j}\,b_j(i)\,\rho_{kj}(\tau_j-\tau_k)+\sum_{j>k}\sqrt{2E_j}\,b_j(i-1)\,\rho_{jk}(\tau_k-\tau_j)\Big\}+n_k(i)\end{aligned} \tag{4}$$

In which the signal in the large bracket is the MAI of asynchronous DS-CDMA system. $\rho_{jk}(\tau_k-\tau_j)=\frac{1}{T}\int_{iT+\tau_k}^{(i+1)T}c_j(t-iT-\tau_j)\,c_k(t-iT-\tau_k)\,dt$ and $\rho_{kj}(\tau_j-\tau_k)=\frac{1}{T}\int_{(i+1)T}^{(i+1)T+\tau_k}c_j(t-iT-\tau_j)\,c_k(t-iT-\tau_k)\,dt$ represents the partial correlation function of the spreading code between client and client. $n_k(i)=\int_{iT+\tau_k}^{(i+1)T+\tau_k}n(t)\,c_k(t-iT-\tau_k)\,dt$ is the correlation noise. The matrix expression of formula (4) is[11]:

$$\mathbf{y}(l)=\mathbf{R}(-1)\mathbf{W}\mathbf{b}(l+1)+\mathbf{R}(0)\mathbf{W}\mathbf{b}(l)+\mathbf{R}(1)\mathbf{W}\mathbf{b}(l-1)+\mathbf{n}(l) \tag{5}$$

In which $\mathbf{W}=\mathrm{diag}\left(\left[\sqrt{2E_1},\cdots,\sqrt{2E_K}\right]\right)$, $\mathbf{b}(l)=\left[b_1(l),\cdots,b_k(l)\right]$, $l=\{-M,\cdots,M\}$, $\mathbf{R}(0)$ and $\mathbf{R}(1)$ are $K\times K$ matrix, and element (j,k) is show in formula (7). So $\mathbf{R}(-1)=\mathbf{R}^T(1)$. After Z-transformation to formula (5), we get:

$$\mathbf{Y}(z)=\left[\mathbf{R}^T(1)z+\mathbf{R}(0)+\mathbf{R}(1)z^{-1}\right]\mathbf{W}\mathbf{b}(z)+\mathbf{n}(z)=\mathbf{H}(z)\mathbf{b}(z)+\mathbf{n}(z) \tag{6}$$

As shown in formula (6), to use the asynchronous decorrelation DS-CDMA MUD system, the main point is to get the linear operator $\mathbf{L}$. Before this, the address of $\mathbf{R}(0)$ and $\mathbf{R}(1)$ should be acquired. And then compute the inverse of $\mathbf{H}$. Compared with synchronous DS-CDMA system[6], the complexity of computation is greatly increased, so a simplified method is needed.

$$\begin{aligned}&\mathbf{R}_{jk}(0)=1,\ j=k, \quad \rho_{jk}\left(\tau_k-\tau_j\right),\ j<k, \quad \rho_{kj}\left(\tau_j-\tau_k\right),\ j>k\\ &\mathbf{R}_{jk}(1)=0,\ j\geq k, \quad \rho_{kj}\left(\tau_j-\tau_k\right),\ j<k\end{aligned} \tag{7}$$

3.2 Quasi-synchronous Decorrelation MUD Algorism

From formula (3) we can find out that in the case $\tau_1\leq\tau_2\leq\cdots\leq\tau_K\ll T$, $\frac{1}{T}\int_{(i+1)T}^{(i+1)T+\tau_k}\sum_{j=1}^{K}\sqrt{2E_j}b_j(i)c_j\left(t-iT-\tau_j\right)\cdot c_k\left(t-iT-\tau_k\right)dt$ in formula (3) is far less than $\frac{1}{T}\int_{iT+\tau_k}^{(i+1)T}\sum_{j=1}^{K}\sqrt{2E_j}b_j(i)c_j\left(t-iT-\tau_j\right)\cdot c_k\left(t-iT-\tau_k\right)dt$, so it could be ignored. Therefore, formula (3) could be simplified as follow, in which $\tau_{x1}=\tau_x-\tau_1$.

$$\begin{aligned}y_k(i)&=\frac{1}{T}\int_{iT+\tau_k}^{(i+1)T}\sum_{j=1}^{K}\sqrt{2E_j}b_j(i)c_j\left(t-iT-\tau_j\right)\cdot c_k\left(t-iT-\tau_k\right)dt\\ &=\frac{1}{T}\int_{\tau_{k1}}^{T}\sum_{j=1}^{K}\sqrt{2E_j}b_j(i)c_j\left(t-iT-\tau_{j1}\right)\cdot c_k\left(t-iT-\tau_{k1}\right)dt\end{aligned} \tag{8}$$

This restriction of the simplifying can be reached, for example, all the transmitters use the same inter-clock (such as GPS timing clock) to ensure the time consistent of each chip transmitting. Then when the distance of nodes between each other is not far and transmission chip rate is not too quick, transmission delay of each node will differ little and far shorter than the chip length.

And formula (8) could be realized by this method: use the first peak correlation value of the matched filter as zero point to calculate delays of other peak correlation values, which is τ_x. Then calculate the summation of transmitters' partial correlation value. In this way, we can provide initial parameters for MUD. The error loss of correlation calculus will lead to the loss of output SNR, but latter analysis will show that this loss could be acceptable. By the simplifying process described above, formula (3) could be simplified as follows:

$$y_k(i)=\sqrt{2E_k}b_k(i)+\sum_{j<k}\sqrt{2E_j}b_j(i)\rho_{jk}\left(\tau_k-\tau_j\right)+\sum_{j>k}\sqrt{2E_j}b_j(i)\rho_{kj}\left(\tau_j-\tau_k\right)+n_k(i) \tag{9}$$

So the linear decorrelation factor of quasi-synchronous MUD is $\left[\mathbf{R}(0)\right]^{-1}$ and the output of matched filter decision is $\hat{\mathbf{b}} = \mathrm{sgn}\left(\left[\mathbf{R}(0)\right]^{-1}\mathbf{Y}\right)$. In this way, MAI is eliminated, but the computational complexity is much less complex than asynchronous system.

Based on the analysis given above, MUD method in quasi-synchronous DS-CDMA network is promoted. Compared with asynchronous MUD, the amount of computation is lowered (especially when the number of clients is large) which is meaningful to engineering realization. Meanwhile, by adopting MUD technology, the impact of MAI is eliminated, the detection ability of spreading code as address code is guaranteed, and parallel data transmission of transmitters is also realized. In this way, it provides support for protocol design that is based on this.

4 Protocol Simulation and Performance Analysis

4.1 Quasi-synchronous Decorrelation MUD Performance

Aimed at the quasi-synchronous decorrelation MUD algorism proposed in section three, bit error rate (BER) of nodes in the network is adopted to measure the channel quality, to ensure that the proposed MUD performance can satisfy the requirement of inhibiting MAI of the designed protocol.

Let background noise of channel be σ^2, element of the partial correlation matrix $\left[\mathbf{R}(0)\right]^{-1}$ is r_{ij}, the output noise power of node *k* after matched filter decision is $E_k = \sigma^2 \sum_{i=1}^{K} r_{ik}^2$. As for node *k*, the correlation time is shortened by τ_{k1}, so the output signal power decision is $(T - \tau_{k1}) E_k / T$. Then receiving BER of this node is:

$$\eta_k = Q\left(\sqrt{SNR_{out}}\right) = Q\left(\sqrt{(T - \tau_{k1}) E_k \Big/ T\sigma^2 \sum_{i=1}^{K} r_{ik}^2}\right) \tag{10}$$

In which: $Q(x) = 1\big/\sqrt{2\pi} \int_x^{\infty} e^{-u^2/2} du$.

Assuming $\sigma^2 = 1$, $E_1 = E_2 = \cdots = E_K = 15$ (output SNR is 11.8dB), using 31 bit Gold sequence as spreading code[12], $\tau_{k1} = (k-1)T/31K$. Then, according to reference [6], the BERs of synchronous decorrelation and the conventional receiver can be obtained, and BER of quasi-synchronous decorrelation can be calculated by formula (10). So BERs versus the change of node number is shown in figure 4.

From figure 4, it can be concluded that when there are fewer nodes, the performance of quasi-synchronous BER is worse than conventional single user receiver. This is mainly because that the influence of MAI is smaller than the influence of background noise at this time, while the process of decorrelation magnifies the background noise, therefore, the SNR is decreased. However, when there are more nodes, the BER performance of conventional receiver deteriorates

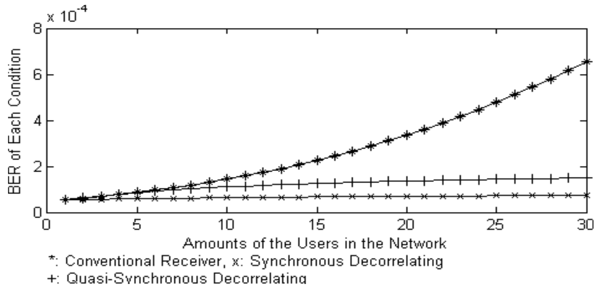

Fig. 4. BER comparing of different receiver

rapidly while the BER of quasi-synchronous decorrelation process is nearly smooth, and is similar to the performance of synchronous decorrelation process. The correlation time of quasi-synchronous process is shortened which leads to the BER difference between synchronous process and quasi-synchronous process. But the BER loss is acceptable. This can fully satisfy the proposed protocol's requirement for the performance of code division channel. Moreover, it is a better choice to take both realizability and MUD performance into consideration.

4.2 Network Simulation Model Description

To validate the implementation of the designed protocol, this paper uses OPNET to simulate it. The node model is comprised of sending process and receiving process, the state machine is shown in figure 5. In the sending process, state IDLE implements idle waiting and destination node selection operations. The state DETECT and CONNECT implement channel listening and link establishing operations. The state SEND implements data (information data and control data) transmission and reply request operations. At last, the state DISCONN implements link disconnection operation. The receiving process uses RECV state to implement information data and control data receiving operation, frame continuity detection operation and controlling the sending process to implement corresponding operation according to the state of the received data.

To validate the protocol performance in different cases, different simulation environments are established by OPNET based on the process models in figure 5. The

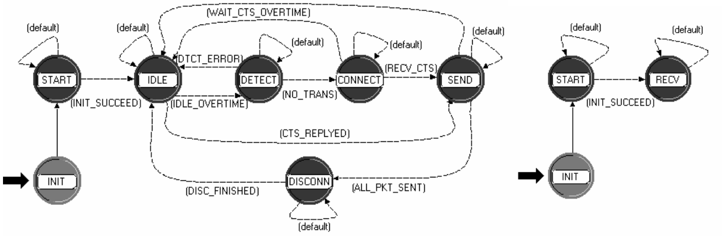

Fig. 5. Model of transmitting process (left) and model of receiving process (right)

simulation environment is described as follows: N nodes distribute uniformly on a 100 meters ×100 meters plane; the data transmission rate is 1000 packets/s; the length of each packet is 36 bits; each node selects destination node randomly; after link establishment, source and destination nodes transmit 100 packets respectively to each other, and a length L buffer window is used to detect the received data. During the process of data transmission, if there is one bit error in one packet, this packet will be requested to retransmit. The received packet is stored in the buffer window in sequence, and the one that is out of the sequence number will be dropped. After one data transmission, the source and destination nodes will be idle for $\bar{t}+\Delta t_{rand}$ (Δt_{rand} is a uniform distribution in [-0.02, 0.02], so $\bar{t}$ is the average idle period of each nodes), and then start new link and transmission. The transmission power of nodes in the network is set to 1.5W, and the background noise power is set to 0.1W. Because the network only overcasts a short range, the signal power loss during transmission could be ignored, so the SNR of each receiver is 11.8dB ($10\log(1.5/0.1)$). Therefore, the environment settings in OPNET of the receiving BER are the same as described in section 4.1. To be simple, we simulate the BER described in section 4.1 by Matlab, and modify the settings of pipeline stage in OPNET with the result. Based on the parameters settings above, by modifying the number of nodes N, average idle time and buffer window length L, simulated and compared the throughput of protocol adopting MUD with the throughput of the protocol without MUD and the throughput of CSMA/CD (CSMA with Carrier Detection) protocol[13] in different environments. Each simulation time of throughput is 5 minutes, and each simulation time of dropout rate is 30 minutes.

4.3 Analysis of Simulation Results

When $L=1$, and $N=25$, the curves of throughput changed with average idle time $\bar{t}$ is shown in figure 6(left). It is seen from the figure that the probability of collision during link establishment and invalid waiting time is reduced by adopting the link establishment mechanism of the proposed protocol. Therefore, when the business increases, after the throughput of the protocol using MUD reaches the peek value, it will then drop a little compared with the significant drop of the throughput of the protocol without MUD. This is mainly because, the numbers of nodes transmit at the same time increase with business, and the BER will also increase, which leads to the drop of throughput. However, after using MUD, the influence of BER will be reduced, so multi node pairs could communicate at the same time. Therefore, the throughput of the network using this protocol is far larger than the throughput of CSMA/CD which only one node pair could occupy the channel. And when $\bar{t}=0.5$, $L=1$, the curves representing the throughput changed with the number of nodes in the network is shown in figure 6 (right). In the same way, as this proposed protocol allows multi node pairs to transmit data at the same time, its throughput is much larger than CSMA/CD at the same condition. Moreover, with the influence of BER produced by users number increasing, after the throughput reaches the peak value, it also drops a little, compared with the significant drop of throughput of the protocol without MUD.

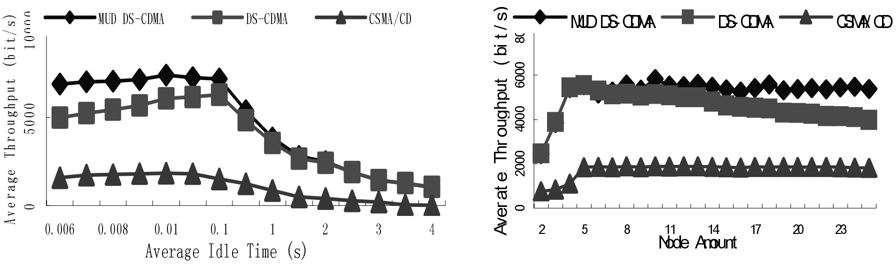

Fig. 6. Throughout comparing of MUD DS-CDMA, DS-CDMA and CSMA/CD in different network businesses (left) and in different network scale (right)

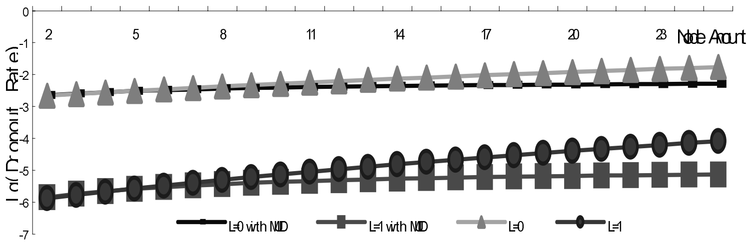

Fig. 7. Dropout rate comparing of MUD DS-CDMA and DS-CDMA at different length of transmission window

When $\bar{t}=0.5$, $L=0$, $L=1$, the curves representing the dropout rate changed with nodes number changing are shown in figure 9. It can be seen that the dropout rate is greatly decreased by setting buffer window in the communication process and adopting the retransmitting mechanism proposed in this paper. This is because that with the checking window, only when there are successive error packets and it is beyond the window the packets will be dropped. Therefore, the retransmission and MUD mechanisms adopted in the protocol in this paper could decrease the dropout rate. However, with the increase of window length, the processing delay and complexity will be increased too. Therefore, both the dropout rate and window length should be considered in practical application.

5 Conclusion

By analysis of the performance of the proposed protocol, we can find that the designed link protocol and MUD methodology realizes the networking of a decentralized all-connected network, decreasing the accessing waiting delay, increasing the throughput and lowering the retransmitting rate and dropout rate. Therefore, it can fulfill the application requirement of quickly establishing temporary wireless network in a small area.

As the proposed network protocol in this paper is based on all-connected network, wide area application should still be researched. Meanwhile, the requirement of this protocol for MUD performance is strict, therefore, the processing complexity, detecting error performance and other aspects should be improved, for example, to adopt a better spreading code selection method to reduce the cross correlation of inter codes, and improve the MUD performance.

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