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Achieve Significant Throughput Gains in Wireless Networks with Large Delay-Bandwidth Product

Jiamian Wang, Weidong Liu *

Department of Computer Science and Technology, Tsinghua University, Beijing 100084, China

Abstract

Traditionally, Bandwidth-Delay Product can be used to measure the capacity of network "pipe" between two nodes. However, in multi-hop wireless networks, Bandwidth-Delay Product cannot reveal the network condition accurately. In this paper, we define a new metric called Delay-Bandwidth Product (DBP) for wireless networks, which measures the capacity of a one-hop pipe in wireless networks. Wireless networks with a large DBP can have a throughput larger than the one based on traditional understanding. We propose a scheduling algorithm aims for making use of the large DBP in wireless networks. We then design simulations to figure out how much throughput gains can be achieved in wireless networks, with small DBPs and large DBPs respectively. The simulation result demonstrates that we can achieve significant throughput gains in wireless networks with large DBP.

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Keywords: wireless networks; wireless sensor networks; throughput; delay-bandwidth product

1. Introduction

Traditionally, Bandwidth-Delay Product (BDP) is used to measure the capacity of an end-to-end network pipe [1]. It is defined as the product of a data link's capacity and its end-to-end delay. BDP is a key factor for the performance of traditional networks; for instance, in networks with a large BDP, the standard TCP needs

E-mail address: wangjm11@mails.tsinghua.edu.cn, liuwd@tsinghua.edu.cn.

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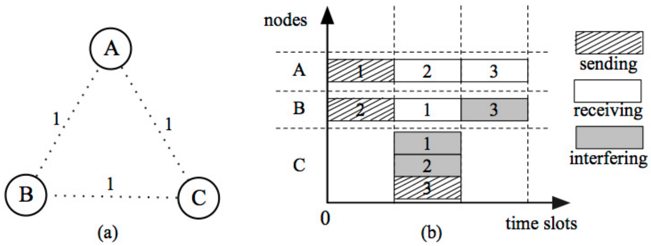

Fig. 1. Three nodes in a broadcast domain (a) and the transmission schedule (b). It can be verified that all the packets can be successfully transmitted and received without any collision.

to be modified to fully utilize the underlying available bandwidth [2].

However, some wireless networks employ "hop-by-hop" transmitting scheme instead of "end-to-end" scheme, such as wireless sensor networks. As a result, traditional Bandwidth-Delay Product cannot reveal the performance of wireless network accurately. In this paper, we define a new concept called *Delay-Bandwidth Product* (DBP) for wireless networks, which is defined as the product of the average delay of one-hop propagation and bandwidth in the wireless network. It measures the capacity of a *one-hop* pipe in wireless networks. In wireless networks with a large DBP, even a one-hop pipe may contain more than one packet propagating simultaneously. What's more, since most wireless sensor networks employ hop-by-hop transmitting schemes, DBP may be a key factor to the performance of those networks.

Traditionally, we believe nodes within a single broadcast domain in wireless networks can transmit and receive at most one packet per packet transmission time (PTT) [3]. In this work, we find wireless networks with a large DBP can have a throughput larger than the one based on traditional understanding. Since even a one-hop pipe is able to contain more than one packet propagating simultaneously, we can make use of it.

The example in Fig. 1(a) presents the findings intuitively. Three nodes *A*, *B* and *C* are in the same broadcast domain. The propagation delay between every two nodes is one PTT. After dividing time into continuous time slots in units of PTT, consider three transmissions: packet #1 from *A* to *B* in slot 0, #2 from *B* to *A* in slot 0, and #3 from *C* to *A* in slot 1. It is easy to verify all the packets can be successfully transmitted and received without any collision, as shown in Fig. 1(b).

This example implies that we may achieve throughput gains by making use of large DBP. However, the example is too ideal to apply in practical circumstances for two reasons. First, the nodes must be placed carefully; second, even if the nodes are placed carefully, a small shift of location will ruin the transmission. Fortunately, we propose a novel transmitting scheduling algorithm in Section 3, which not only adapts to arbitrary node locations, but also is tolerant to location shifting.

We now discuss wireless networks which can have a throughput larger than the one based on traditional understanding. Let η denote the Delay-Bandwidth Product. For simplicity, we consider η in units of packets rather than bits, and we assume each packet has the same length of 200 bytes. Clearly, the scenario in Fig. 1 can happen if and only if $\eta \geq 1$.

We begin with the IEEE 802.11b/g networks, which has a propagation speed of $3*10^8$ m/s, an average bandwidth of usually less than 50Mbps and an average distance between two neighbor nodes being less than 100m. The DBP is less than 0.01 packets. Due to the very small η, the scenario in Fig. 1 cannot be constructed.

We move on to find other wireless networks with $\eta \geq 1$. Generally, a large DBP can be caused by a large propagation delay or a large bandwidth. A large propagation delay can be further caused by a long distance or a low propagation speed. We can give several examples.

Spacecraft networks. In spacecraft networks [4] or Interplanetary Internet, with a propagation speed of $3*10^8$ m/s, an average bandwidth of 200kbps and an average distance between two neighbor nodes larger than

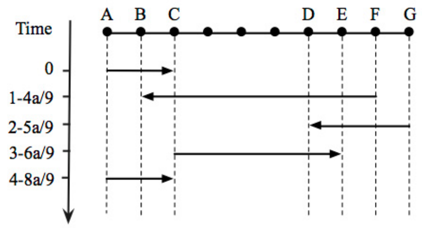

Fig. 2. An example showing that throughput gains larger than zero always exist in wireless networks, no matter how small η is.

5,000km, the DBP η is about 2 packets. The large DBP is mainly caused by the long distance between nodes.

Underwater acoustic networks. With a very low propagation speed of 1,500 m/s, an average bandwidth around 20kbps and an average distance between two neighbor nodes around 1200m [5], the DBP η is about 10 packets. The large DBP is mainly caused by the large propagation delay.

Therefore, a higher performance may be achieved in a variety of scenarios. In this work, we attempt to provide a new understanding about DBP in wireless networks and reveal its impacts on throughput.

Our contributions are three-fold. First of all, we reveal that a throughput larger than the one based on traditional understanding can be achieved in various kinds of wireless networks, which is closely related to delay-bandwidth product (DBP), a new metric we defined for wireless networks to measure the capacity of a one-hop pipe in wireless networks. Secondly, for a single broadcast domain in wireless networks with a large DBP, we propose a novel scheduling scheme which can make use of large DBP. Thirdly, we build simulation and analyze how a large DBP can improve network performance.

The remainder of this paper is organized as follows. Section 2 reveals the impacts of DBP on the throughput. In Section 3 we propose a scheduling algorithm to leverage the large DBP in wireless networks. Section 4 simulates how DBP influences the throughput. Finally, this paper is concluded in Section 5.

2. Impacts of the delay-bandwidth product

A major concern is that why large Delay-Bandwidth Product enlarges throughput in wireless networks. For simplicity, we consider it in a single broadcast domain. First, we propose several constraints.

In order to successfully receive a packet, the receiver has to spend one PTT to receive the packet. During the time, no other signal is allowed to interfere with the receiver. Also, the packet from a transmitter will interfere with other nodes sooner or later for a PTT, except for the targeted node.

Some constraints are different as the result of a large DBP. First of all, a node can transmit packets while being interfered by packets not targeted for it, which called *interfered transmitting*. Moreover, it is possible that multiple interference are overlapping together, which called *interference overlapping*.

Both interfered transmitting and interference overlapping will make throughput gains possible. For example, in slot #1 of Fig. 1 (b), we can see interference overlapping -- interference from node *A* and *B* are overlapped together at node *C*. Besides, we can see interfered transmitting -- when node *C* is interfered, it is transmitting instead of doing nothing.

One key issue is that how does Delay-Bandwidth Product influence the throughput gains we can achieve. We show the quantitive relationships between throughput gains and DBP via the next two theorems.

Theorem 1. *For any wireless network with any η>0, situation which have throughput gains always exists.*

Proof. We only need to build a scenario which can achieve throughput gains with any η > 0. Consider the cases with η ≤ 1/2, since it can be applied to any cases with η > 1/2.

Consider the following example in a line segment of length *a* = η, as shown in Fig. 2. Here nodes *A*, *B*, *C*,

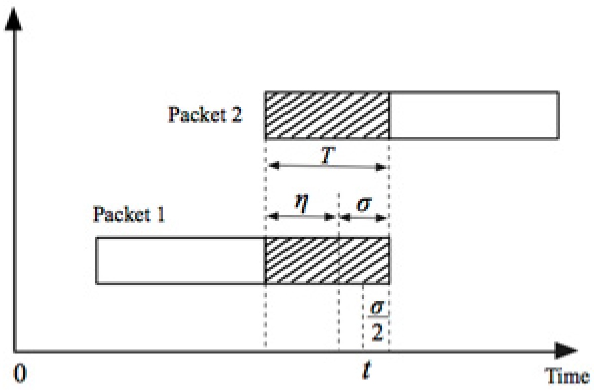

Fig. 3. Two packets with a simultaneous transmission time larger than η.

D, *E*, *F* and *G* are located at positions 0, $a/9$, $2a/9$, $6a/9$, $7a/9$, $8a/9$ and a, respectively. Each arrow represents a packet transmission. Transmission starts at the time given in the time axis in the left.

Here, four packets will be transmitted and received within $4 - 8a/9$ successfully. So the throughput gains are $4 / (4 - 8a/9) - 1 > 2a/9$. Hence for any $\eta > 0$, situation with a larger throughput always exists. □

Throughput gains can be always obtained even in networks with any small DBP, although it may be very small. Moreover, when the DBP gets to zero, the gains approaches to zero as well. In fact, we find that the maximal throughput gains achievable is limited by the DBP, which is given in the next theorem.

Theorem 2. *When $\eta \leq 1/2$, the maximal throughput gains are no more than 2η.*

Proof. First, we proof by contradiction that the simultaneous transmission time for any two packets should be no more than η.

Suppose we have two packets as shown in Fig. 3 and their simultaneous transmission time T is larger than η, say $T = \eta + \sigma$, $0 < \sigma \leq 1 - \eta$ (when they start transmitting in the same instant, $T = 1$ and $\sigma = 1 - \eta$). Now consider time t, the beginning instant of their last $\sigma/2$ simultaneous transmission time. The receivers of packet #1 and packet #2 at t must be receiving the signal of packet #1.The reason is that at t the first bit of packet #1 has already been propagated more than η away, which means all the points within the single broadcast domain with a size η have received the first bit. At the same time, the transmitter of packet #1 at t is still transmitting its remaining bits. So the receivers of packet #1 and packet #2 at t must be receiving the signal of packet #1. Similarly, the receiver of packet #1 and packet #2 at t must be receiving the signal of packet #2. Hence collisions happen at t for both of the receivers of packet #1and packet #2. So the simultaneous transmission time for any two packets should be no more than η.

Now, as $\eta < 1/2$, it is easy to know at most two packets could simultaneously transmit packets. Otherwise, there must be two packets whose simultaneous transmission time is larger than η. Further, any packet could at most have its first and last η time transmitting signal simultaneously with other packets. Therefore, the networks could at most transmit one packet during a time interval of $1 - \eta$ on average. So the throughput gains are no more than $1 / (1 - \eta) - 1 = \eta / (1 - \eta) \leq 2\eta$, when $\eta \leq 1/2$.

In sum, DBP is a crucial influencing factor for the throughput gains in wireless networks.

3. Scheduling algorithm

For wireless networks with large DBP, it is possible to enlarge the throughput. Now given a wireless network with large DBP, how can we make use of it? In this section, we propose a scheduling algorithm, which is not only very simple, but also perfect fair.

In general, there are two key principles of our scheduling algorithm.

(1) The algorithm takes turns scheduling all the nodes, ensuring the fairness and simplifies the scheduling;

(2) For each node, the packet will be transmitted in the first available slot, to maximize the performance.

Traditionally, an available time slot for transmitting should satisfies criteria (C1)-(C5) listed below.

(C1) For the sender: the sender itself must be neither receiving nor transmitting in this slot.

(C2) For the receiver: the receiving process will last for 1 PTT. The receiver must be idle during this time, which means the receiver must not be transmitting, receiving, or interfered.

(C3) For other nodes: the signal of the transmition will certainly black other nodes for 1 PTT soon or later. The signal must not interfere with other nodes receiving their own packets.

(C4) About interferences: interferences cannot be overlapped.

(C5) About transmitting: interfered transmitting is not allowed.

However, in wireless networks with large DBP, criteria (C4) and (C5) are no longer necessary. In fact, both interfered transmitting and interference overlapping are the keys to make throughput gains possible.

Now we give a detailed description of scheduling algorithm. We model the network as a directed graph $G(V, E)$, where V is the set of nodes within a single broadcast domain, $|V| = n$, and E is the set of directed links among nodes. Assume the data are grouped into packets of identical size and, all packets have the same PTT. Each node v generates r_v packets, and each packet has its destination node. All these packets must be transmitted in sequence. For simplicity, we let the length of a time slot equal to one PTT.

The algorithm first create an n-row matrix to store the scheduling results. Each element in it may be one of the following statuses: 'TX' - The corresponding node will transmit in this slot; 'RX' - will receive signal; 'IN' - will be interfered by other signal; 'NA' - not scheduled. Note that the number of columns is not fixed; it grows as the algorithm operates.

Then the algorithm enumerates all the nodes and schedules at which slot the node transmits its first packet. As to every specific node v, if there is no packet to be sent from it, the algorithm simply skips this node and then begins to schedule node v+1 (if v is the last node, then jump to the first node); otherwise, algorithm searches the time slots for the first available one for transmitting, according to the criteria listed earlier in this section. Once the available slot is found, the algorithm marks this slot of node v as 'TX'. Moreover, the corresponding slots of the receiver and the other nodes should be marked as 'RX' and 'IN' as well.

One key issue in the algorithm is that since the distance between nodes may not be integers, the signals reached to other nodes may cut across two consecutive time slots. The solution is to mark both the two consecutive time slots. For instance, say there are two nodes A and B, with a distance of $|AB| = 2.3$ PTT. If node A transmits a packet to B in time slot 2, the signal will reach node B by slot 4.3, and lasts until slot 5.3. So the algorithm marks both slot 4 and 5 of node B as "RX". For circumstances when the distance between two nodes is integer, we mark both the receiving or interfered slot along with the bordered two slots. For instance, if the distance between sender node A and receiver node B is 2 PTT, and node A transmits in slot 2, then the algorithm marks slots 3, 4, 5 of B as "receiving". Doing so ensures that we schedule in units of slot, which is simple and reasonable. Besides, since in most cases the reaching signal cuts across two time slots, slight shifting of nodes locations will not ruin the scheduling. What's more, if the location shifts sharply, we can mark more consecutive slots to ensure robustness, at the expense of degrading performance.

4. Simulation and performance evaluation

In this section, we build simulations to confirm the theoretical analysis.

A simulation scenario consists of n nodes in one broadcast domain of wireless network. The locations of the nodes are generated randomly. Say the identical packet size is p, and the average bandwidth of the wireless network is k. Given the scenario, the Delay-Bandwidth Product η can be worked out. First, we calculate the average one-hop distance l in these scenario (in units of the distance which signal propagated in one PTT), so the average one-hop delay of the wireless network is l * (p / k). Thus, the Delay-Bandwidth Product is $\eta = l * (p / k) * k / p = l$ packets.

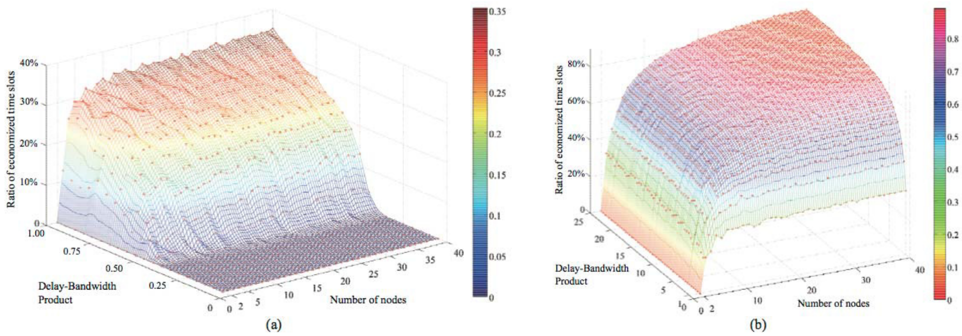

Fig. 4. Simulation result when Delay-Bandwidth Product η ≤ 1 (a) and η ≥ 1 (b). This figure indicates that almost no throughput gains can be achieved when η is considerably small; however, when η > 1/2, the bigger η and n are, the more throughput gains can be achieved. The vertical axis represent the ratio of time slots which can be economized if we take advantage of the characteristic of large DBP in wireless networks, the higher the better. For instance, 40% in the vertical axis means the network can transmit same amount of packets with only 60% of time slots as traditional understanding, if we make use of large DBP.

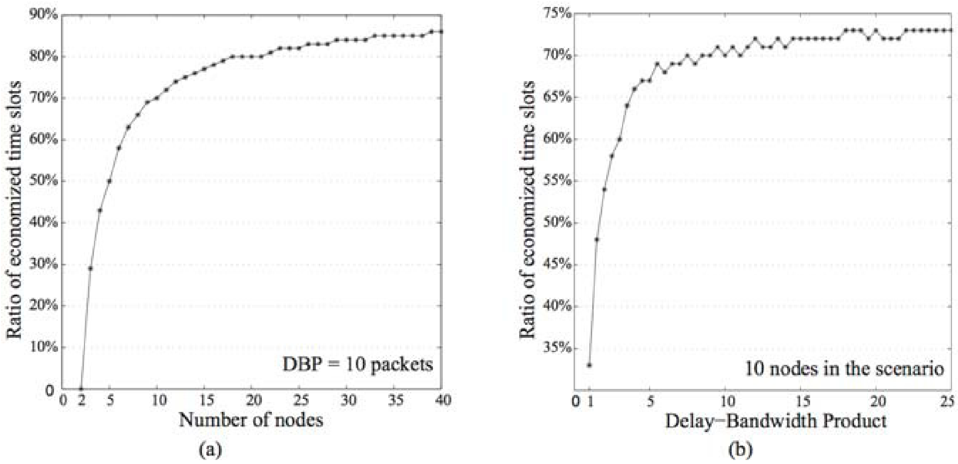

Fig. 5. Simulation result when η = 10 (a) and n = 10 (b). Given Delay-Bandwidth Product η, the more number of nodes, the higher performance can be achieved; similarly, given the number of nodes n, the bigger Delay-Bandwidth Product is, the better performance can be achieved. The vertical axis represent the ratio of time slots which can be economized if we take advantage of the characteristic of large DBP in wireless networks, the higher the better.

For each scenario, we run two simulations. One follows the criteria under traditional understanding, which no interference overlapping and interfered transmitting are allowed. The other one follows the criteria under the understanding proposed in this paper. Say the traditional scheduling scheme cost x time slots to successfully transmit all the packets, and the new scheduling scheme needs y slots. Then $\beta = (x - y) / x$ is the ratio of time slots that can be economized if we take advantage of the large DBP in wireless networks. We emphasize here that for each η and n, more than 100 different scenarios are simulated, in order to figure out the average economized slots ratio. Luckily, when η and *n* are fixed, the ratio is quite steady, therefore the average ratio is a characteristic metric for valuing the improvement of performance.

The results are shown in Fig. 4. Some important conclusions can be concluded below.

(1) If there are only two nodes in a single broadcast domain, no throughput gains can be achieved, no matter how large the DBP is. It is reasonable since no interference appears in these scenarios.

(2) When there are more than two nodes in a single broadcast domain, a higher throughput may be achieved. And, as the number of nodes increases, the throughput gains gets larger. It makes sense: more nodes there are, more chances to make use of interferences.

(3) As we discussed in Section 2, even when η is quite small, a higher throughput can be achieved, although it may be very small. Especially when $\eta < 1/2$, almost no throughput gains can be made.

(4) On one hand, given the number of nodes, the bigger η is, the higher performance may be achieved. On the other hand, given DBP, the more number of nodes, the higher performance may be achieved as well. Fig. 5(a) shows the relationship between the economized time slots ratio and number of nodes in wireless networks with $\eta = 10$. Fig.5 (b) shows the relationship between the economized time slots ratio and DBP η when there are 10 nodes within one broadcast domain.

In summary, significant throughput gains can be achieved in networks with a large DBP. In a typical scenario of underwater acoustic sensor network with a DBP $\eta = 10$ and 4 nodes within a broadcast domain, about a half of transmitting time may be economized to transmit the same amount of packets, if we make use of the large DBP.

5. Conclusion and Future Work

In this paper, we reveal that a throughput larger than the one based on traditional understanding can be achieved in various kinds of wireless networks. We point out that the throughput gains are closely related to a large delay-bandwidth product (DBP), a new metric we defined for wireless networks which measures the capacity of a one-hop pipe in wireless networks.

We then propose a simple but very effective scheduling algorithm aiming to make use of the large Delay-Bandwidth Product in wireless networks. This algorithm is simple, fair and serviceable.

In the last section of this paper, we set up simulations. Several important conclusions can be summarized from the simulation result, which conform to the analysis earlier discussed in this paper very well.

Some work can be done in the future. Especially, for those networks with a large Delay-Bandwidth Product, a formal and theoretical formalization and analysis is needful to reveal more intrinsic qualities.

References

[1] K.Chen, Y.Xue, S.H.Shah, K.Nahrstedt, Understanding bandwidth-delay product in mobile ad hoc networks, Computer Communications 27(10)(2004) 923–934.

[2] T.Lakshman, U.Madhow, The performance of tcp/ip for networks with high bandwidth-delay products and random loss, Networking, IEEE/ACM Transactions on 5 (3) (1997) 336–350.

[3] L. G. Roberts, Aloha packet system with and without slots and capture, SIGCOMM Comput. Commun. Rev. 5 (2) (1975) 28–42. doi:10.1145/1024916.1024920.
URL http://doi.acm.org/10.1145/1024916.1024920

[4] M. A. Bergamo, High-throughput distributed spacecraft network: architecture and multiple access technologies, Computer Networks 47 (5) (2005) 725– 749.

[5] I.F.Akyildiz, D.Pompili, T.Melodia, Underwater acoustic sensor networks: research challenges, Ad hoc networks 3(3)(2005)257–279.