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A note on CSMA performance in underwater acoustic networks

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ABSTRACT

Carrier sensing MAC protocols have limited utility in underwater acoustic networks because the propagation delay is not small relative to the packet duration. A recent publication shows simulated results that would appear superior to those predicted by accepted theoretical analysis. We compare the simulated performance against theoretical predictions, then provide an independent simulation of the same scenario and conclude that the CSMA results originally published are equivalent to the CSMA results that would be observed with no propagation delay. This is a reminder of the importance of independently verified results, even for simulations. We then provide what we consider to be corrected results and outline an effort to further validate underwater acoustic MAC protocols with both simulation and in-water tests.

1. Introduction

A recent publication [1] in this journal performed simulations of CSMA operating underwater (on page 2022, Fig. 8, CSMA results are labelled ALOHA after CSMA-ALOHA). We include this figure here as Fig. 1. These simulation results appear to substantially exceed Kleinrock's widely accepted mathematical analysis of CSMA [2]. This letter discusses the difference between these published simulation results, the mathematical analysis, and our own simulation results. It then draws conclusions regarding the risks of simulation results. The key problem for CSMA in underwater acoustic networks is that the propagation delay in the network is not small relative to the packet duration. In Kleinrock and Tobagi's notation, the relative propagation delay, a, is large, so the current channel state as sensed by any potential transmitter is poorly correlated with the future channel state at the receiver, or 'decisions based on partially obsolete data are deleterious' [2]. Consequently, CSMA should not perform as well as it does with small relative propagation delay.

2. The difference between the simulation and theory

The subject network [1] was made up of 10 nodes at 1 km spacing, transmitting packets to a single sink sitting at the centre. Our understanding of the network layout is shown in Fig. 2. The data rate of the transceiver is 4800 bps, packet size is 600 bytes, and traffic load was λ bps per node. The network was not fully connected, so a node on one side of the sink may not hear a transmitting node at the other side of the sink, which means there will be hidden nodes in the network. The thrust of the paper [1] was to investigate the impact of the irregular propagation pattern modelled by Bellhop in contrast to the simpler, but unrealistic, lossy unbounded spreading model labelled as Urick. Besides CSMA, the DACAP and the T-Lohi MAC protocols were also simulated under the identical network scenario. However, the simulation result for CSMA with the Urick model is the focus of this letter.

The simulation results for the CSMA do not match Kleinrock and Tobagi's analysis in [2], even accounting for the layout and limited number of nodes. Kleinrock and Tobagi's analysis shows that CSMA throughput can be expressed as a formula of

$$S = \frac{Ge^{-aG}}{G(1+2a)+e^{-aG}} \tag{1}$$

where a is the relative propagation delay with respect to the packet duration (propagation delay/packet duration) and G is the normalised offered traffic load with respect to the channel capacity [2]. We reference Kleinrock and Tobagi's analysis as Fig. 3 (Fig. 3 on page 1405 of [2]) to compare with Fig. 1. The vertical axes of both figures are the same, being the normalised throughput with respect to the channel capacity. The horizontal axes differ in both concept and scaling. To aid comparison, we select the upper bound of Kleinrock and Tobagi's theory curves which has no relative propagation delay ($a = 0$) and replot as Fig. 4 on a linear horizontal axis. As Fig. 5, we relabel the horizontal axis of Fig. 1 to the normalised offered load with respect to the channel capacity after Kleinrock and Tobagi so that Fig. 4 and 5 share the same concept of horizontal

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axes. Comparing both figures, we see that the simulation results for CSMA underwater in [1] exceed Kleinrock and Tobagi's analysis of the upper bound of the throughput of CSMA (the circumstance with no propagation delay) at least within the offered traffic load region shown in [1]. The reader should note that Fig. 5 shows near perfect throughput for CSMA on a network with high relative propagation delay at normalised offered load up to 40%, i.e. the network is suffering very few collisions.

Kleinrock and Tobagi [2] implied that when the relative propagation delay a is larger than 1, the carrier sensing provides nodes with partially obsolete information, which degrades the performance of CSMA to a level bearing some similarity to pure ALOHA. Indeed, Fig. 3 shows the utility of CSMA declining substantially for any non-small value of a. We now calculate the relative propagation delay a in the scenario in [1]. We assume a sound propagation speed in water of 1500 m/s. The packets are 600 bytes, and the data rate is 4800 bps, so the packet duration is $(600 \times 8)/4800 = 1$ s. The distance between the nodes and the sink ranges between 500 m and 2062 m. Therefore, a is in the range 0.33–1.37. The actual propagation range is unclear, so the extent of the hidden node problem is uncertain. Selecting $a = 0.33$ and $a = 1$ from Kleinrock and Tobagi's theoretical curves in Fig. 3, we observe that the peak of both curves are 0.3035 and 0.1444 respectively. We should reasonably expect the peak of the throughput of the scenario in [1] to be between these values. However, in Fig. 1 from [1], CSMA using the Urick model achieves a throughput exceeding 0.4 and rising, which appears uncomfortably high.

The theoretical analysis on the network layout (Fig. 2) will further demonstrate that when the relative propagation delay a is large underwater, the carrier sensing will not be as useful as it is in terrestrial radio networks (networks with negligible propagation delays). The subject network has a single destination D, so carrier sensing at a potential interfering node I is based on completely obsolete data when the propagation delay from the source S, to I and then to D ($\tau_{s,i,d}$) is equal to, or greater than the packet duration d plus the propagation delay from S to D ($\tau_{s,d}$). Here we calculate the ratio of

$$u = \frac{d - (\tau_{s,i,d} - \tau_{s,d})}{d} \tag{2}$$

as the measurement of the usefulness of the carrier sensing at the interferer for the interference detection and avoidance, being the probability that carrier sensing at the interferers will prevent the collision (at the destination) with the sensed packet which was sent by a source node. This usefulness ratio in the networks with negligible relative propagation delay ($a = 0$) is 1 meaning that carrier sensing is working perfectly to prevent collisions. For example, node 4 (I) has a packet ready to send when node 1 (S) is transmitting. So the usefulness of node 4's carrier sensing for node 1's transmission is $u = \{(4800/4800) - [(1414/1500 + 1118/1500) - (2062/1500)]\}/(4800/4800) = 0.6867$, which means that the usefulness of node 4's carrier sensing to prevent collision at node 11 with this packet transmitted by node 1 is only 0.6867. Table 1 shows this usefulness ratio for each of the node sensing every other node's transmission. Since the overall average usefulness ratio u of the entire network is only 0.2201 as shown in the table, it is obvious that the CSMA is far less useful than it is with negligible propagation delay where $u = 1$. In other words, the simulation result in [1] which shows CSMA

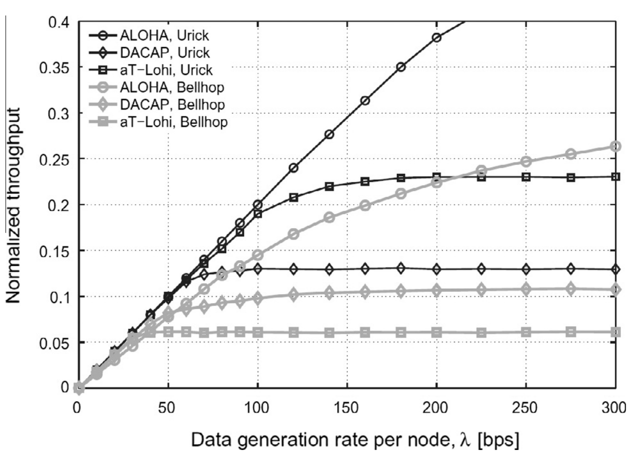

Fig. 1. Simulation results in [1].

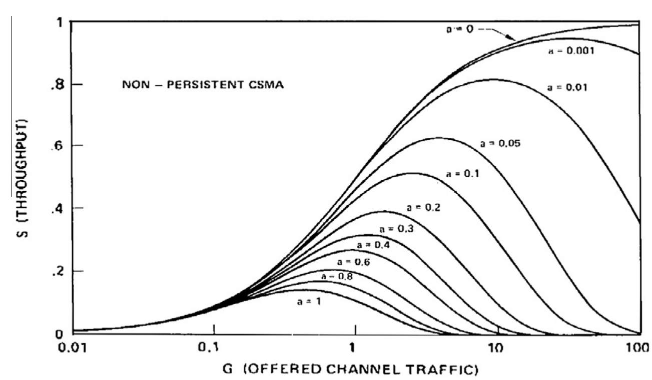

Fig. 3. Kleinrock and Tobagi analysis of NP-CSMA [2].

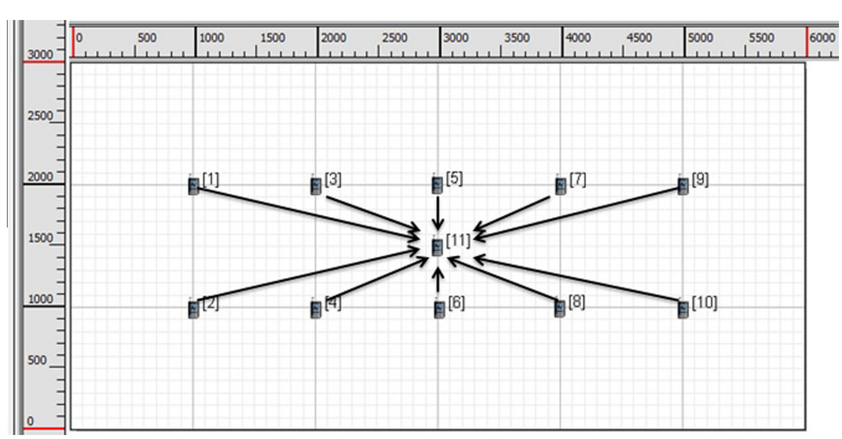

Fig. 2. Network layout.

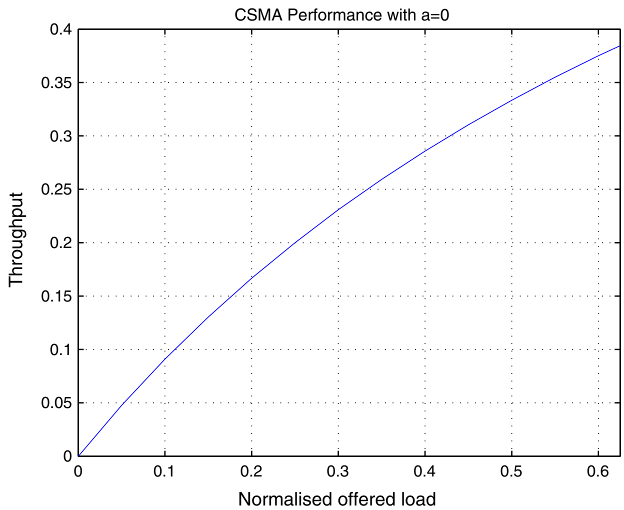

Fig. 4. Kleinrock and Tobagi NP-CSMA upper bound with $a = 0$.

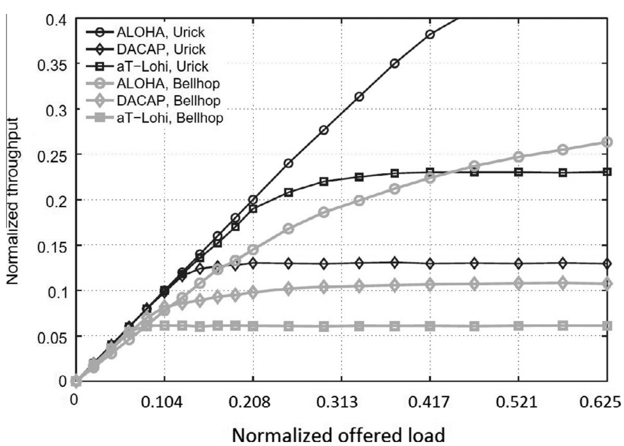

Fig. 5. Normalised horizontal axis of Fig. 1.

performance equivalent to that in terrestrial radio networks ($u = 1$) is problematic.

3. Independent simulation results

To explore what performance the CSMA should have when the relative propagation delay is large, we carried out our own simulations with the identical network scenario in [1], but using the Qualnet simulation tool instead of ns-2. We used a free-space transmission model which is equivalent to the Urick model, and simulated CSMA in both a terrestrial network using the radio propagation speed in air (3e8 m/s) and an underwater network using the sound propagation speed in water (1500 m/s). The signal transmission range and interference range are both set to be 3300 m.

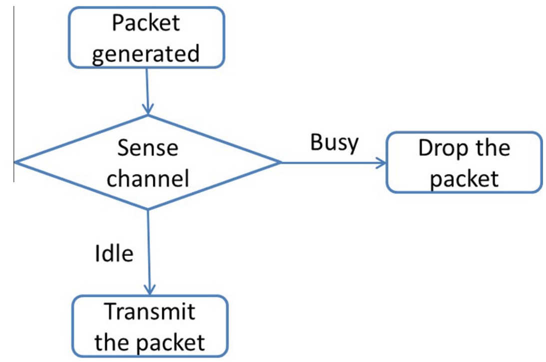

Fig. 6. Flow diagram for implemented non-persistent CSMA.

The CSMA protocol we implemented in Qualnet was non-persistent CSMA. The flow diagram is as shown in Fig. 6. All the packets are generated at each node according to Poisson distribution (with the mean packet interval 10:2:150 s). When a node has a packet to send, it senses the channel instantaneously. If the channel is idle, it sends out the packet. Otherwise, the packet is dropped. Neither a back off strategy after the unsuccessful transmission nor a feedback strategy (ACK) after a successful transmission is used. Since the packets are generated according to Poisson distribution, the dropping of the unsuccessfully transmitted packets has the same effect with the random back off strategy when the channel is sensed busy. We believe this makes for clear results highlighting only the effect of channel propagation delay by minimising the chance of variations in protocol implementation.

We first simulate the CSMA in a free-space radio network using Kleinrock and Tobagi's offered load concept, which is the arrival rate of packets at the MAC layer from the upper layers and the rescheduled packets normalised to the channel capacity. We note that not all these packets will result in a successful transmission. The simulation result is shown in Fig. 7. As the radio propagation speed was used, the relative propagation delay a approaches 0 for the simulated scenario. Therefore, we add a solid curve in Fig. 7 which is Kleinrock and Tobagi's theory result when $a = 0$ for comparison. Kleinrock and Tobagi's theoretical analysis was carried out without considering hidden node problems, which would cause a divergence from our results at high offered load. To compare our simulation results to [1], we adjust our offered

Table 1
Probability of the usefulness of carrier sensing by interferers of the subject network.

Interference \ Source	1	2	3	4	5	6	7	8	9	10
1	x	0.3333	0	0	0	0	0	0	0	0
2	0.3333	x	0	0	0	0	0	0	0	0
3	0.96	0.6867	x	0.3333	0	0	0	0	0	0
4	0.6867	0.96	0.3333	x	0	0	0	0	0	0
5	0.7067	0.5493	0.7467	0.4707	x	0.3333	0.7467	0.4707	0.7067	0.5493
6	0.5493	0.7067	0.4707	0.7467	0.3333	x	0.4707	0.7467	0.5493	0.7067
7	0	0	0	0	0	0	x	0.3333	0.96	0.6867
8	0	0	0	0	0	0	0.3333	x	0.6867	0.96
9	0	0	0	0	0	0	0	0	x	0.3333
10	0	0	0	0	0	0	0	0	0.3333	x
mean value	0.3596	0.3596	0.1723	0.1723	0.037	0.037	0.1723	0.1723	0.3596	0.3596
overall mean	0.2201									

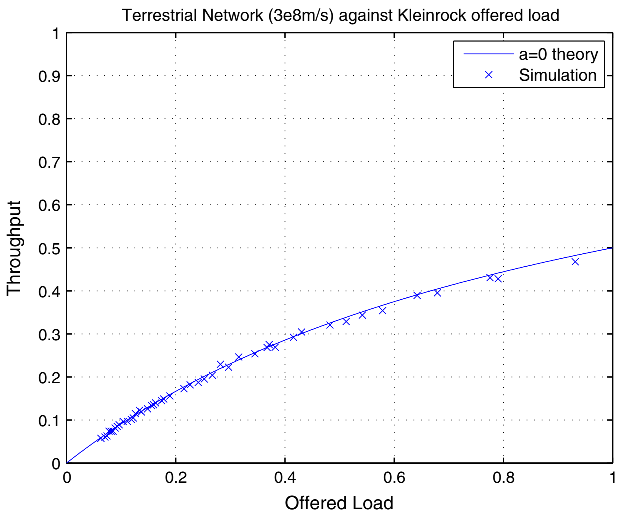

Fig. 7. Throughput against offered load.

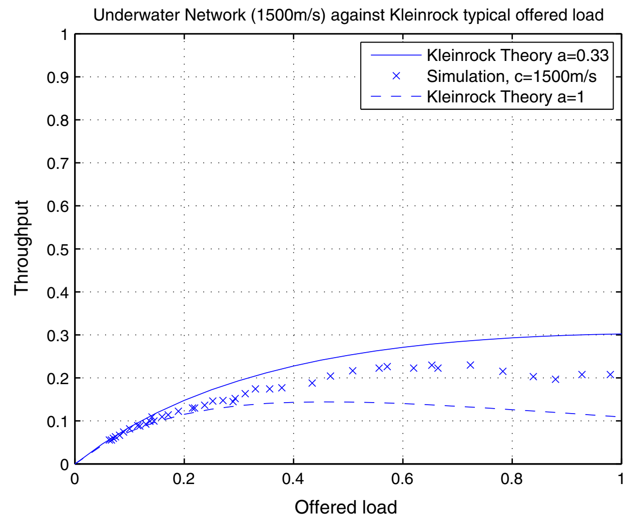

Fig. 9. Underwater simulation with propagation speed of 1500 m/s.

load definition to be the rate of the successful packet transmissions with respect to the channel capacity, the "Transmitted Load". In other words, this "Transmitted Load" measures the number of the packets that are transmitted via the physical channel. The rescheduled packets are only counted as they are transmitted. The result is shown in Fig. 8 which matches Fig. 5 (CSMA simulation in [1] using the Urick model). This means that their results are consistent with the case when a approaches 0 (i.e. very small relative propagation delay). We emphasise that the simulated results for the 10-node network are a close match for Kleinrock's analysis, notwithstanding that Kleinrock assumed a network with an infinite number of randomly located nodes.

We re-simulate the scenario with the sound propagation speed of 1500 m/s, and Fig. 9 shows this simulation result plotted against Kleinrock and Tobagi's offered load along with Kleinrock and Tobagi's theory analysis with a of 0.33 and 1. Our simulation result meets our expectation that the throughput should be between the $a = 0.33$ and $a = 1$ lines. Our simulation result plotted against the "Transmitted Load" (ie not counting packets that are dropped due to carrier detection) is shown in Fig. 10 with comparison to the CSMA simulation results from [1]. This indicates that even being measured with the (best case) "Transmitted Load", the results from [1] are unreasonably high. From our simulation results in Figs. 9 and 10, it can be found that CSMA throughput performance in underwater networks is much lower than in terrestrial radio networks even when Urick or 'free-space' propagation is assumed. This is primarily because the relative propagation delay a is not small, so carrier sensing is performed on at least partially obsolete data which means that the carrier sensing technique no longer reliably avoids collisions.

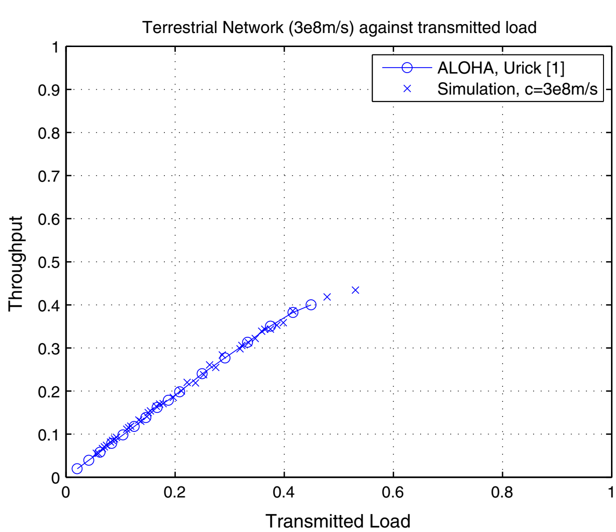

Fig. 8. Throughput against transmitted load.

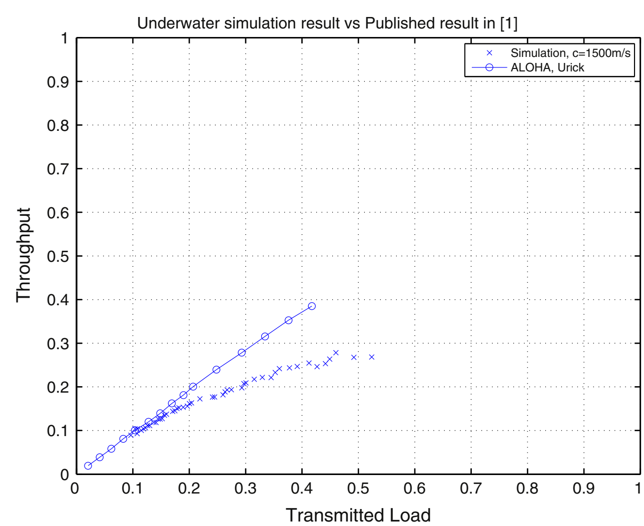

Fig. 10. Underwater simulation measured by "Transmitted Load".

4. The difference between "Offered Load" and "Transmitted Load"

From Fig. 8, it can be seen that our simulation results with a low latency network plotted against "Transmitted Load" match the original result in [1]. This "Transmitted Load" does not count the packets that were dropped or backed off if the channel was sensed busy. Through private communication we understand that the "ALOHA" results in [1] were actually 1-persistent CSMA, thus the Transmitted Load should approach the Offered Load, differing only perhaps by packets remaining in buffers at the end of the simulation period. All forms of persistent CSMA retransmit backed-off

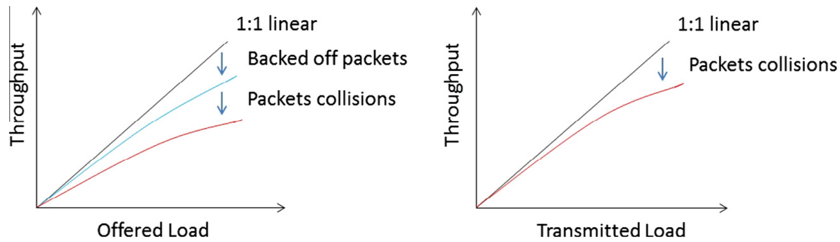

Fig. 11. Channel capacity comparison between offered and transmitted load.

packets in some interval following the back-off – with the various forms of persistence affecting the distribution of these retransmissions. We can then draw two conclusions about persistent-CSMA. Firstly, the Offered Load approximates the Transmitted Load almost precisely. Secondly, the traffic density following a back-off exceeds the traffic density prior to a back-off. This is because the backed-off packet must be added to the load still being offered from high layers of the network stack. It therefore follows that since the probability of a collision is a monotonically increasing function of offered load, the throughput of any persistent-CSMA scheme at a given offered load, cannot exceed the throughput of non-persistent-CSMA at the same transmitted load (see Fig. 11). Fig. 10 therefore represents an upper limit on CSMA performance on the subject network, irrespective of the persistence scheme.

5. 1-Persistent CSMA

In private correspondence, the original authors of [1] have indicated that their "ALOHA" results were obtained using 1-persistent CSMA. It has been suggested by others that the variation of the published 'ALOHA' results from those we obtain using non-persistent CSMA is due to the 1-persistence. We believe that our analysis has the highest clarity when presented with non-persistent CSMA, since there are multiple implementation variations for persistent-CSMA. In particular, Kleinrock and Tobagi [2] assume that nodes using 1-persistent CSMA should retransmit as soon as the channel is sensed idle – leading to potential race conditions. In p-persistent CSMA, the sender transmits a frame with a probability p if the medium becomes idle, thereby avoiding the race condition. In both cases, we argue that the throughput cannot exceed our non-persistent CSMA case normalised for Transmitted Load. However, for the avoidance of doubt, we devote this section to reporting on a re-run of our simulations and analysis for the 1-persistent case to illustrate that the results are as we have previously expected.

When accounting for 1-persistent CSMA, the simulation results for the CSMA in [1] do not match Kleinrock and Tobagi's analysis in Section IV-C of [2], even accounting for the layout and limited number of nodes. Kleinrock and Tobagi's analysis shows that the throughput of 1-persistent CSMA can be expressed as a formula of

$$S = \frac{G[1 + G + aG(1 + G + aG/2)]e^{-G(1+2a)}}{G(1 + 2a) - (1 - e^{-aG}) + (1 + aG)e^{-G(1+a)}} \tag{3}$$

We reference Kleinrock and Tobagi's analysis as Fig. 12 (Fig. 5 on page 1407 of [2]) to compare with Fig. 5. Again, we select the upper bound of Kleinrock and Tobagi's theory curves which has no relative propagation delay ($a = 0$) and replot as Fig. 13 on a linear horizontal axis. Comparing Fig. 13 with Fig. 5, once again, we see that the simulation results in [1] reach and even slightly exceed Kleinrock and Tobagi's analysis of the upper bound of the throughput of 1-persistent CSMA (the circumstance with no propagation delay) at least within the offered traffic load region shown in [1]. This once again demonstrates that Fig. 5 shows near perfect

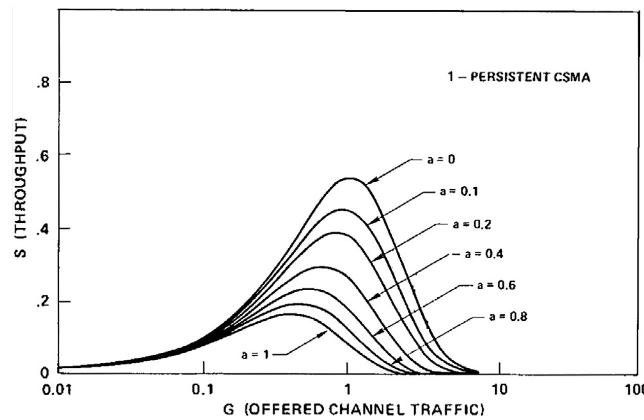

Fig. 12. Kleinrock and Tobagi analysis of 1-persistent CSMA [2].

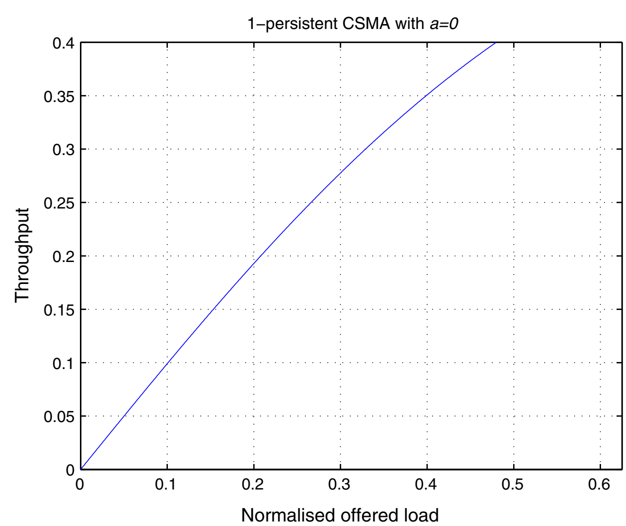

Fig. 13. Kleinrock and Tobagi 1-persistent CSMA upper bound with $a = 0$.

throughput for CSMA on a network with high relative propagation delay at normalised offered load up to 40%, i.e. the network is suffering very few collisions.

As discussed in Section 2, the relative propagation delay a is in the range 0.33 to 1.37. Selecting $a = 0.33$ and $a = 1$ from Kleinrock and Tobagi's theoretical curves of 1-persistent CSMA in Fig. 12, we observe that the peak of both curves are 0.3222 and 0.164 respectively. We should reasonably expect the peak of the throughput of the scenario in [1] to be between these values. However, in Fig. 1 from [1], CSMA achieves a throughput exceeding 0.4 and rising, which appears unreasonably high.

We re-run our simulation for 1-persistent CSMA using the Qualnet simulation tool with a free-space transmission model and simulated 1-persistent CSMA in both a terrestrial network using the radio propagation speed in air (3e8 m/s) and an underwater network using the sound propagation speed in water (1500 m/s). We also leave the signal transmission range and interference range the same with the non-persistent case (3300 m).

The 1-persistent CSMA protocol we implemented in Qualnet is described as the flow diagram in Fig. 14. Again, packets are generated at each node according to Poisson distribution (with the mean packet interval 10:2:150 s). When a packet is generated, it is firstly pushed into the queue. Then the node senses the channel instantaneously. If the channel is idle, it sends out the packet and deletes the packet from the queue. Otherwise, the node keeps sensing the channel. From then on, as soon as the channel is sensed to be idle, the node sends out the packet and deletes the packet from the queue. After finishing sending the packet, the node checks the queue. If the queue is not empty, the node checks the channel status and repeats the steps. Feedback strategy (ACK) for successful transmission is not used.

We first simulate the 1-persistent CSMA in a free-space radio network using Kleinrock and Tobagi's offered load concept. The simulation result is shown in Fig. 15. Therefore, we add a dotted curve in Fig. 15 which is Kleinrock and Tobagi's theory result when $a = 0$ for comparison. To compare our simulation results to [1], we add the results published in [1] on the same figure. It can be found that our simulation results matches Kleinrock and Tobagi's theory ($a = 0$) and the CSMA results originally published in [1] are consistent with the theory at low offered load region. We also replotted the simulation results using the 'Transmitted Load' concept. The result is the same as the case when Kleinrock and Tobagi's offered load concept is used. This is because all the packets generated are pushed into the queue and finally transmitted. The number of packets generated is equal to the number of packets transmitted.

We re-simulate the scenario with the sound propagation speed of 1500 m/s, and Fig. 16 shows this simulation result plotted against Kleinrock and Tobagi's offered load along with Kleinrock and Tobagi's theory analysis with a of 0.33 and 1. Our simulation result meets our expectation that the throughput should be between the theoretical lines for $a = 0.33$ and $a = 1$. Again, our simulation results plotted against the 'Transmitted Load' concept has the same result with the case when Kleinrock and Tobagi's offered load concept is used. From our 1-persistent CSMA simulation results shown in Fig. 16, it can be seen that CSMA throughput performance in underwater network is much lower than in terrestrial radio networks even when Urick or 'free-space' propagation is assumed, and irrespective of the persistence scheme. Again, paraphrasing [2], this is because the relative propagation delay a is not small, so carrier sensing is performed on at least partially obsolete data which means that the carrier sensing technique no longer reliably avoids collisions.

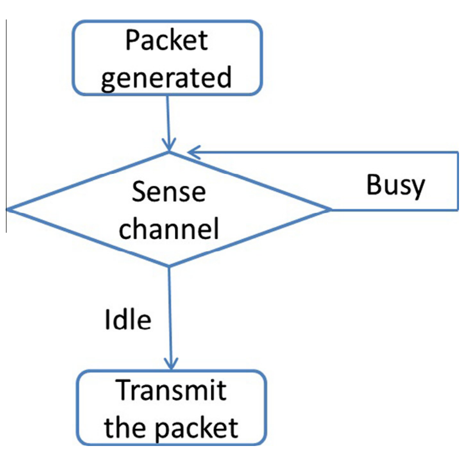

Fig. 14. Flow diagram for implemented 1-persistent CSMA.

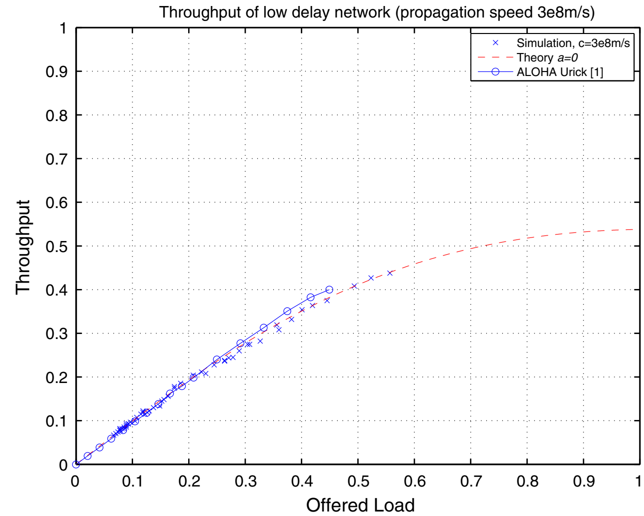

Fig. 15. 1-persistent CSMA in terrestrial radio network.

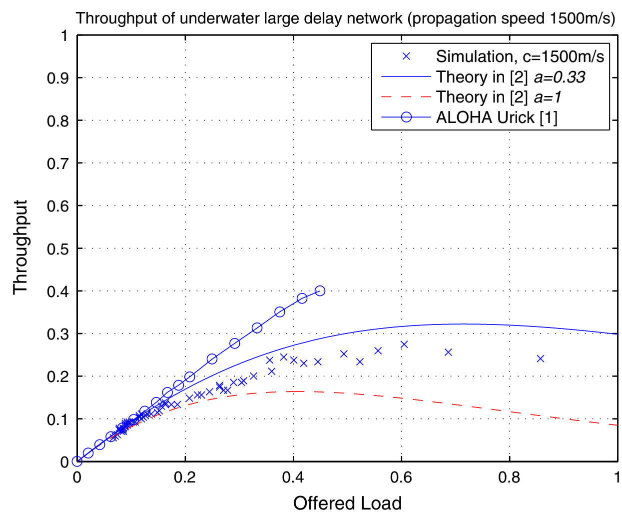

Fig. 16. Underwater simulation with propagation speed of 1500 m/s.

6. Conclusion

We have shown above that the subject paper [1] gives a very high throughput for CSMA compared to the theoretical analysis in [2]. The throughput achieved in [1] fits well with the case where relative propagation delay is low, but diverges markedly from any simulation or analysis we can provide for a network with high relative propagation delay a. We have also analysed and simulated the 1-persistent CSMA case, which again does not explain the original results. These uncomfortably high simulation results may lead readers to draw the incorrect conclusion that the CSMA can perform as well on high propagation delay underwater links as it does in radio networks. The quoted results appear consistent with a very small relative propagation delay (a approaching 0) and with "Transmitted Load" as the horizontal axis, however we cannot replicate them using the speed of sound in water (a is large). This is consistent with 1-persistent CSMA at low offered load with a approaching 0.

In a broad context, we are reminded that simulations are prone to errors, so validation by independent groups with different tools is invaluable. Further, due to the limitations of simulations, real underwater experiments are needed to validate the performance and feasibility of the proposed MAC protocols. This work is part of a progressive plan to develop our underwater acoustic MAC study from theory to simulation and then to validation of existing proposed protocols in a physical network of up to eight underwater acoustic nodes. From a coherent set of studies, simulations and fresh and salt water trials, we will ensure that the differences between theory, simulation and the real performance are well understood. This will advance the ongoing global development of underwater MAC protocols on a sound basis.

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