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Propagation-Delay-Aware Analytical Comparison of CSMA/CA-Based MAC Mechanisms for Underwater Acoustic Sensor Networks

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Abstract

Underwater acoustic sensor networks require distributed medium access despite long propagation delay, limited bandwidth, and variable channel conditions. This study used a propagation-delay-aware analytical framework in MATLAB to compare conventional CSMA/CA, UW-CSMA/CA, adaptive Network Allocation Vector (NAV) CSMA/CA, and cross-layer OFDM CSMA/CA in a single-hop star network. The model uses a fixed aggregate network load, explicit competing-load scaling, a one-way link-level propagation ratio, and a conservative MAC-level ratio based on maximum inter-source separation. Common equations are applied for packet error, contention, collision, throughput, successful-packet delay, and source-side energy. All mechanisms are first evaluated with equal physical-layer reliability, followed by an OFDM reliability sensitivity analysis. The results show that adaptive-NAV CSMA/CA provides the highest throughput and per-attempt packet success probability and the lowest delay and energy cost across the evaluated node counts, distances, and offered loads. Cross-layer OFDM becomes competitive only when a defensible reliability improvement is introduced. Future work should validate the framework using packet-level simulation, BER/PER analysis, statistical validation, and sea-trial calibration.

Keywords: Underwater acoustic networks; CSMA/CA; propagation delay; adaptive NAV; OFDM; medium access control.

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مقارنة تحليلية لآليات CSMA/CA الواعية بتأخير الانتشار في الشبكات الصوتية تحت الماء

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الملخص

تتطلّب شبكات الاستشعار الصوتية تحت الماء آليّاتٍ موزَّعة للنفاذ إلى الوسط، على الرغم من طول زمن تأخير الانتشار، ومحدوديّة عرض النطاق، وتغيّر ظروف القناة. تستخدم هذه الدراسة إطارًا تحليليًا واعيًا بتأخير الانتشار، مُنفَّذًا باستخدام MATLAB، لمقارنة أربع آليّات هي CSMA/CA :التقليدي، وUW-CSMA/CA، و CSMA/CA المزود بمتجه تخصيص الشبكة التكيُّفي (NAV) ، و CSMA/CA متعدّد الطبقات المعتمد على OFDM ، وذلك ضمن شبكة نجمية أحادية القفزة.

يعتمد النموذج على حملٍ شبكي إجمالي ثابت، وتحجيمٍ صريح لحمل التنافس، ونسبة انتشار أحادية الاتجاه على مستوى الوصلة، إلى جانب نسبة محافظة على مستوى طبقة MAC مبنيّة على أقصى مسافة ممكنة بين مصادر الإرسال. كما تُطبَّق معادلات موحَّدة لتمثيل خطأ الحزم، والتنافس على الوسط، واحتمال التصادم، والإنتاجية، وزمن تأخير الحزمة الناجحة، واستهلاك الطاقة عند جهة المصدر.

وتُقيَّم الآليّات أولًا بافتراض موثوقية متساوية للطبقة الفيزيائية، ثم يُجرى تحليل حساسية لدراسة أثر التحسّن المفترض في موثوقية OFDM. وتُظهر النتائج أن CSMA/CA المزود بـ NAV التكيُّفي يحقّق أعلى إنتاجية وأعلى احتمال لنجاح الحزمة في كل محاولة، مع أقل زمن تأخير وأدنى كلفة للطاقة ضمن أعداد العقد والمسافات والأحمال المعروضة التي جرى تقييمها. أمّا CSMA/CA متعدّد الطبقات المعتمد على OFDM فيصبح منافسًا عندما يُفترض تحسّنٌ قابل للتبرير في الموثوقية.

وتوصي الدراسة مستقبلًا بالتحقّق من الإطار المقترح باستخدام المحاكاة على مستوى الحزم، وتحليل BER/PER، والتحقّق الإحصائي، والمعايرة بالاستناد إلى التجارب البحرية.

الكلمات المفتاحية: الشبكات الصوتية تحت الماء؛ CSMA/CA؛ تأخير الانتشار؛ NAV التكيفي؛ OFDM؛ التحكم في النفاذ إلى الوسط.

INTRODUCTION

Underwater acoustic sensor networks support environmental monitoring, offshore infrastructure inspection, oceanographic data collection, surveillance, and autonomous underwater vehicle coordination (Akyildiz et al., 2005; Heidemann et al., 2006). Their medium-access-control layer operates under conditions that differ fundamentally from terrestrial radio networks, including low and distance-dependent bandwidth, severe multipath, Doppler spread, high modem energy consumption, and a sound speed of approximately 1500 m/s (Jiang, 2018; Chen et al., 2014). A 5-km one-way acoustic link therefore introduces approximately 3.33 s of propagation delay before queueing, contention, packet transmission, or acknowledgement delay is considered.

Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) remains attractive because it is distributed, requires limited scheduling state, and accommodates sporadic traffic. Nevertheless, carrier sensing cannot guarantee collision avoidance underwater. A source may sense an idle channel while another transmission is still propagating toward the sink or toward a distant contender. Long request-to-send/clear-to-send exchanges and conservative reservation timers may reduce collisions but consume a substantial part of the available channel time. Underwater designs therefore modify persistence, backoff, reservation intervals, transmit power, or physical-layer adaptation (Peleato and Stojanovic, 2007; Doukkali et al., 2006).

Petrioli et al. (2008) compared several underwater MAC families under different loads and topologies. Keshtgary et al. (2012) evaluated R-MAC, Slotted FAMA, and UWAN-MAC, while Zhao et al. (2013) studied the influence of large relative propagation delay

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on ALOHA, CSMA, and MACA. Pu et al. (2015) compared UW-Aloha, SASHA, and PMAC in real-sea experiments, and Petroccia et al. (2018) evaluated CSMA, T-Lohi, and DACAP during at-sea campaigns. These works establish that no access mechanism is universally superior and that propagation delay, topology, and traffic intensity strongly affect performance.

Although previous comparative studies provide valuable insights, direct comparison across them remains difficult because they employ different network geometries, packet durations, propagation assumptions, modem characteristics, channel models, and offered-load definitions. Moreover, many studies compare protocols from fundamentally different MAC families, making it difficult to isolate the specific benefits of propagation-aware CSMA/CA adaptation. A unified analytical comparison under common assumptions is therefore required to distinguish MAC-layer improvements from advantages introduced by physical-layer reliability assumptions.

This study compares four CSMA/CA-related mechanisms selected to represent different channel-access strategies relevant to underwater acoustic networks. Conventional CSMA/CA is included as the terrestrial carrier-sensing baseline (IEEE, 2024). UW-CSMA/CA represents persistent waiting and propagation-aware deferral (Fang et al., 2010). Adaptive Network Allocation Vector (NAV) CSMA/CA represents propagation-dependent channel reservation and release based on NAV optimisation (Cho et al., 2017). Cross-layer OFDM CSMA/CA represents collision-versus-channel-loss awareness together with an optional physical-layer reliability enhancement (Yin et al., 2015).

These existing mechanisms are used as benchmark approaches and are subsequently implemented and evaluated under a common simulation framework to enable a consistent comparison of their performance.

However, the objectives of this work are summarised as follows:

1. To evaluate and compare the four CSMA/CA-related mechanisms under identical network, traffic, packet, and physical-layer reliability assumptions in terms of

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throughput, per-attempt packet success probability, collision probability, delay, and source-side energy cost.

2. To investigate, through MATLAB sensitivity analysis, how an assumed OFDM physical-layer reliability gain influences the performance and comparative ranking of the evaluated mechanisms.

METHODOLOGY AND EVALUATION SETUP

Network, traffic, and packet model

The network is represented as a circular single-hop star with N static, half-duplex underwater sources and one surface sink represented at its centre. All sources share one acoustic channel and transmit directly to the sink; relaying, mobility, and inter-source forwarding are outside the present scope. The maximum source-to-sink radius is d_{max}. The reported link-level delay and channel-error metrics are evaluated for a source at d_{max}, representing the worst-case operating link. For contention analysis, the maximum possible separation between two sources is conservatively bound by $2d_{max}$. This deterministic geometry avoids dependence on random node-placement seeds while explicitly distinguishing link propagation from inter-source carrier-sensing delay. Figure 1 illustrates the topology.

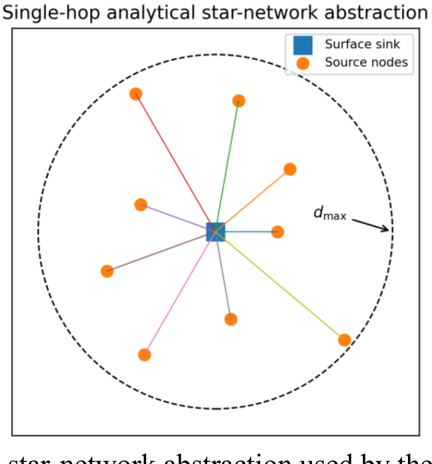

Fig. 1. Single-hop star-network abstraction used by the analytical model.

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Each source generates fixed-length payloads. Let G denote the aggregate normalized offered load generated by the entire network. The aggregate offered payload rate before losses is therefore GR bit/s. For N statistically identical sources, the normalized offered load per source is $g = G/N$. From the perspective of a tagged source, the combined offered load generated by the remaining $N - 1$ contenders is $G_c = (N-1)g = (N-1)G/N$. The competing-load term G_c is used in the contention-intensity, protocol-overhead, and backoff expressions. Thus, increasing N changes the number of independently contending sources while the aggregate network load remains constant. A fixed-per-node-load evaluation is left for future packet-level work. Packet transmission and one-way propagation times are defined in Equations (1) and (2), respectively. Akyildiz et al. (2005).

$$g = \frac{G}{N}, G_c = (N-1)g = \frac{(N-1)G}{N}$$

$$T_{data} = \frac{L}{R} \quad (1)$$

$$T_{\text{prop}} = \frac{d_{max}}{c} \quad (2)$$

where $\boldsymbol{T}_{\mathbf{data}}$is the packet transmission time (s), $\boldsymbol{L}$is the packet length (bits), $\boldsymbol{R}$is the payload data rate (bit/s), $\boldsymbol{T}_{\mathbf{prop}}$is the one-way propagation time (s), $\boldsymbol{d}_{\mathbf{max}}$is the maximum source-to-sink distance (m), and $\boldsymbol{c}$ is the underwater acoustic propagation speed (m/s).

Link-level and MAC-level propagation ratios

Acoustic propagation affects link delay and medium-access contention in different ways. The one-way link-level propagation-to-transmission ratio is defined in Equation (3), where d_{max} is the maximum source-to-sink distance. This ratio measures the severity of one-way link propagation relative to packet transmission duration; it does not represent a round-trip delay or a hidden-terminal interval. Carrier-sensing staleness depends on the

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propagation time between competing sources. For the circular star-network abstraction, the maximum possible source-to-source separation is $d_{ss,max} = 2d_{max}$. A conservative MAC-level propagation ratio is therefore defined in Equation (4). The link-level ratio Γ_{link} is used to characterize one-way propagation severity, whereas Γ_{MAC} is used in the analytical contention and adaptive-reservation expressions. Because Γ_{MAC} is based on the maximum possible source separation, it represents a conservative upper-bound approximation rather than the exact propagation interval of every source pair. Fang et al., 2010; Zhao et al.

$$\Gamma_{link} = \frac{T_{\mathrm{prop}}}{T_{data}} = \frac{d_{max}}{cT_{data}} \quad (3)$$

$$\Gamma_{MAC} = \frac{T_{CS,max}}{T_{data}} = \frac{d_{ss,max}}{cT_{data}} = \frac{2d_{max}}{cT_{data}} \quad (4)$$

where Γ_{link}denotes the link-level propagation-to-transmission ratio, while Γ_{MAC}denotes the conservative MAC-level propagation-to-transmission ratio. $T_{\mathrm{CS,max}}$ is the maximum propagation time between contending sources, and $d_{\mathrm{ss,max}}$is the maximum source-to-source separation, defined as $d_{\mathrm{ss,max}} = 2d_{\mathrm{max}}$for the circular network considered in this study.

The MAC-level ratio assumes the worst-case source-to-source separation $d_{ss,max} = 2d_{max}$ in the circular network and therefore represents a conservative upper bound rather than the propagation delay associated with every contender pair.

Channel-error and collision model

Residual packet loss caused by channel impairments is modelled separately from collision loss. For protocol p, the distance-dependent residual packet-error probability is represented by a monotonic exponential abstraction. The reliability factor χ_p is set to one for every mechanism in the baseline comparison; only the separate OFDM sensitivity analysis varies χ_{OFDM}.

$$P_{e,p}(d_{max}) = 1 - \exp\left[-\frac{\beta}{\chi_p}\left(\frac{d_{max}}{d_0}\right)^m\right] \quad (5)$$

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For each operating point, the MATLAB implementation calculates contention intensity from the competing load G_c, the conservative MAC-level propagation ratio Γ_{MAC}, and the protocol sensitivity η_p, as defined in Equation (6). The use of Γ_{MAC}, rather than the one-way link ratio, reflects the fact that carrier-sensing information may become outdated while a signal propagates between spatially separated contenders.

$$X_p = a_c G_c (1 + a_\Gamma \Gamma_{MAC} \eta_p) \tag{6}$$

The raw collision probability is reduced by the propagation-aware coefficient κ_p and, for adaptive reservation, by the NAV coefficient ν_p. The capped MAC-level ratio $\Gamma_{MAC,c} = \min(\Gamma_{MAC,} \Gamma_{sat})$ prevents the analytical NAV benefit from increasing without bound.

$$P_{c,p}{}^{raw} = (1 - exp[-X_p])(1 - \kappa_p)(1 - \nu_p \frac{\Gamma_{MAC,c}}{\Gamma_{sat}}) \tag{7}$$

$$P_{c,p} = \min\left(P_{c,max}, \max\left(P_{c,min}, P_{c,p}^{raw}\right)\right) \tag{8}$$

Equations (6)– (8) define contention and collision probability at the mechanism level. The MAC-level ratio is a conservative upper bound based on the maximum possible source-to-source separation. Exact collision prediction would require source coordinates, pairwise propagation delays, transmission start times, receiver-side packet-overlap calculations, and an interference or capture model.

Delivery, throughput, delay, and energy metrics

$$q_p = \left(1 - P_{c,p}\right)\left(1 - P_{e,p}\right) \tag{9}$$

In Equation (9), q_p denotes the probability that an individual transmission attempt succeeds after accounting for collision and channel-error loss; it is therefore interpreted as the per-attempt packet success probability rather than the eventual delivery probability after retransmissions. The protocol overhead increases

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with the combined load generated by the competing sources and is represented as $H_p = h_p\,(1 + 0.08G_c)$. The maximum payload service capacity is $C_p = L/(T_{data} + H_p)$. Because G represents the aggregate normalized offered load, the aggregate offered payload rate is GR bit/s, and aggregate successful throughput is given by Equation (10).

$$S_p = \min\left(GR, C_p\right)q_p \tag{10}$$

Assuming independent retransmission attempts that continue until successful reception, the mean number of attempts per delivered packet is $A_p = 1/q_p$. The mean backoff duration depends on the combined load generated by the competing sources and is modelled as $B_p = b_p\,T_{data}\,G_c\,(1 + P_{c,p})$. To represent queueing pressure without claiming a packet-level queue simulation, bounded utilisation is defined as $\rho_p = \min\left\{0.95, G\frac{1 + P_{c,p}}{1 + q_p}\right\}$ and inserted into the service-time approximation in Equation (11). Because channel utilisation depends on the aggregate traffic offered to the shared medium, this approximation uses the total network load G, rather than the competing-load term G_c.

$$Q_p = \frac{\rho_p}{2\left(1 - \rho_p\right)}\left(T_{data} + H_p\right) \tag{11}$$

The channel time occupied by a failed attempt is $F_p = T_{data} + 2T_{prop} + H_p + \delta_{pT\_}ctrl$. Mean successful-packet delay is then calculated using Equation (12).

$$D_p = T_{\mathrm{prop}} + T_{data} + H_p + B_p + Q_p + \left(A_p - 1\right)F_p \tag{12}$$

Source-side energy uses transmit, receive, and idle/listening power states. The energy of a successful attempt is $E_{0,p} =$

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$P_{tx}\,T_{data} + P_{rx}\,T_{ctrl} + P_{id}\,(H_p + B_p + T_{prop})$, whereas the additional failure penalty is $E_{f,p} = P_{id}\,(2T_{prop} + \delta_{pT\_}ctrl)$. The energy cost per kilobit delivered is given by Equation (13).

$$E_{b,p} = \frac{A_p E_{0,p} + (A_p - 1)E_{f,p}}{L} \times 10^6 (mJ/kbit) \quad (13)$$

MATLAB implementation and evaluation setup

The parameters and values used in the MATLAB analytical evaluation are summarised in Table 1.

The MATLAB evaluation uses $N \in \{5, 10, 15, 20, 25\}$, $d_{max} \in \{0.5, 1, 2.5, 5\}$ km, and $G = 0.1, 0.2, \dots, 1.0$. Unless otherwise stated, one variable is swept while the others are fixed at $N = 15$, $d_{max} = 5$ km, and $G = 0.6$. In the node-density sweep, the aggregate normalized offered load G is held constant and divided equally among the N sources. Consequently, the per-source load is $g = G/N$, while the combined load generated by the other $N - 1$ contenders is $G_c = (N - 1)G/N$. Increasing N therefore changes the number of independently contending sources without increasing the aggregate traffic offered to the network. The baseline comparison uses $\chi_p = 1$ for all four mechanisms. The OFDM sensitivity analysis then evaluates $\chi_{OFDM} \in \{1, 1.5, 2, 2.4, 3\}$ while holding all other coefficients constant.

RESULTS AND DISCUSSION

Figure 2 compares the aggregate throughput of the four mechanisms as the number of source nodes increases from 5 to 25, with $d_{\max} = 5$km and $G = 0.6$, under equal PHY reliability. At $N = 5$, the throughputs are 0.768, 0.782, 0.795, and 0.787 kbit/s for conventional CSMA/CA, UW-CSMA/CA, adaptive-NAV CSMA/CA, and cross-layer OFDM CSMA/CA, respectively. At $N = 25$, the corresponding values are 0.760, 0.777, 0.793, and 0.783 kbit/s. The relatively small variation with node count results from keeping the aggregate offered load constant and distributing it among a larger number of sources. Adaptive NAV maintains the

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highest throughput because its propagation-aware reservation reduces unnecessary channel occupation and collision-related losses. This behaviour is consistent with the propagation-aware access principles reported by Fang et al. (2010) and Cho et al. (2017).

Table 1. Parameters used in the MATLAB analytical evaluation.

Parameter	Symbol	Value	Meaning
Aggregate normalized offered load	G	0.1–1.0	Total network load
Per-source normalized load	$g = G/N$	Derived	Equal source share
Competing normalized load	$G_c = (N-1)G/N$	Derived	Load from other sources
Packet length	L	2048 bit	Fixed payload
Payload data rate	R	1700 bit/s	Raw payload rate
Control duration	T_{ctrl}	0.06 s	Control/ACK interval
Sound speed	c	1500 m/s	Acoustic propagation
Collision coefficient	a_c	0.03	Contention scaling
Propagation coefficient	a_Γ	0.42	Propagation contribution
MAC-ratio saturation	Γ_{sat}	3	Caps MAC-level NAV benefit
Collision bounds	$P_{c,min}$; $P_{c,max}$	0.001; 0.92	Probability clipping
Channel parameters	β; m; d_0	0.018; 1.6; 1 km	Distance-error abstraction
Power states	P_{tx}; P_{rx}; P_{id}	18; 2; 0.8 W	Source modem states

Figure 3 shows the mean successful-packet delay as $d_{\max}$increases from 0.5 to 5 km, with $N = 15$and $G = 0.6$, under equal PHY reliability. The delay increases for all mechanisms as propagation distance grows. At 5 km, adaptive-NAV CSMA/CA achieves the lowest delay at 7.78 s, compared with 8.40 s for conventional CSMA/CA, 8.02 s for UW-CSMA/CA, and 8.06 s for cross-layer OFDM CSMA/CA. This improvement results from the lower collision probability of adaptive NAV, which reduces failed transmission attempts and the associated propagation-delay penalty. The observed trend is consistent with Cho et al. (2017) and Zhao et

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al. (2013), who highlighted the importance of propagation delay in underwater MAC performance.

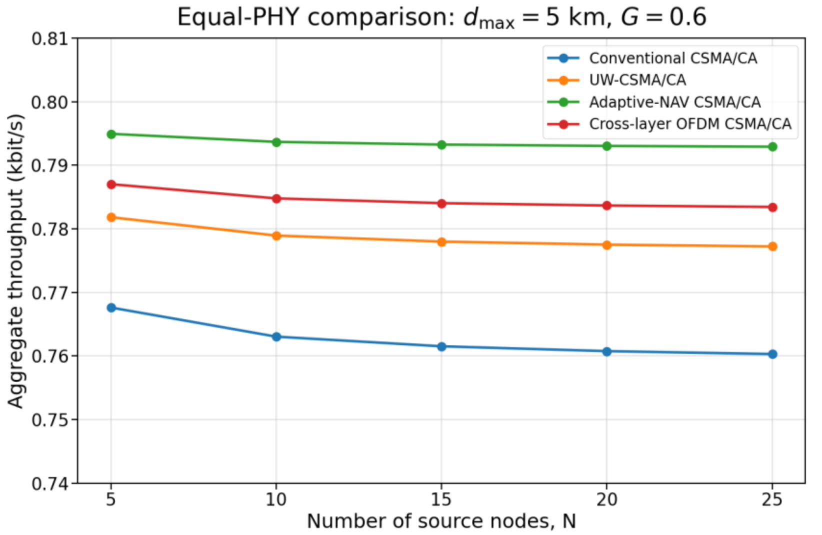

Fig. 2. Aggregate throughput versus node count under fixed aggregate load and equal PHY reliability

Figure 4 presents the per-attempt packet success probability as the aggregate offered load Gincreases from 0.1 to 1.0, with $N = 15$and $d_{\max} = 5$km, under equal PHY reliability. The success probability decreases for all mechanisms as the offered load increases because greater contention leads to more collisions. Adaptive-NAV CSMA/CA maintains the highest success probability across the evaluated load range, mainly due to its more effective propagation-aware collision management. This trend is consistent with previous

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underwater MAC studies showing that increasing traffic load degrades contention-based access performance.

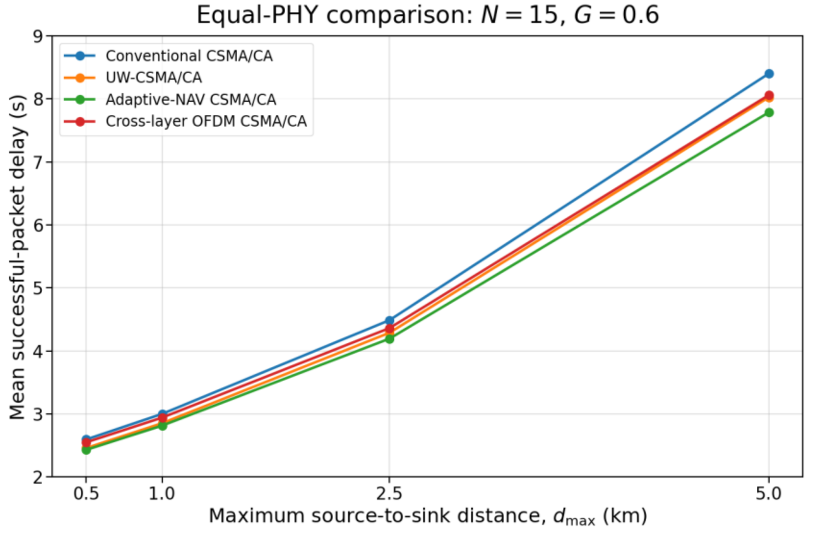

Fig. 3. Mean successful-packet delay versus maximum source-to-sink distance under equal PHY reliability (N = 15, G = 0.6).

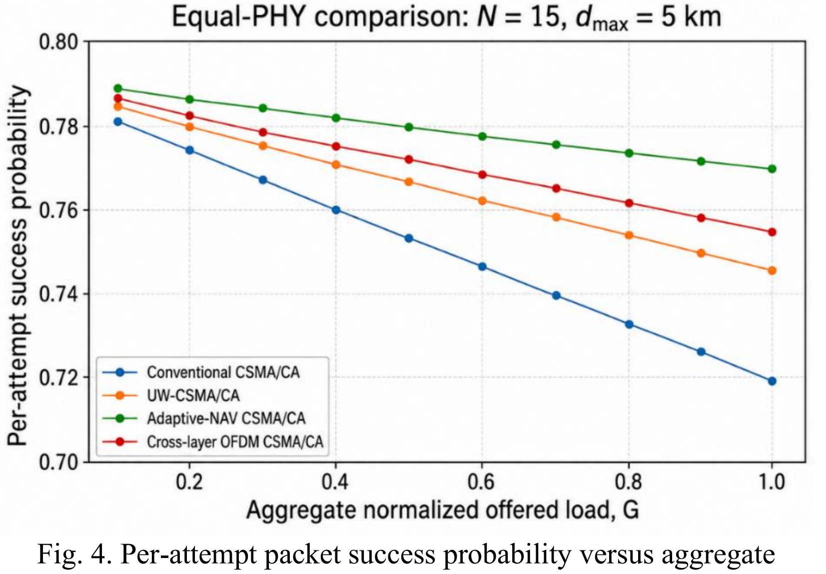

Fig. 4. Per-attempt packet success probability versus aggregate normalized offered load under equal PHY reliability (N = 15, d_{max} = 5 km).

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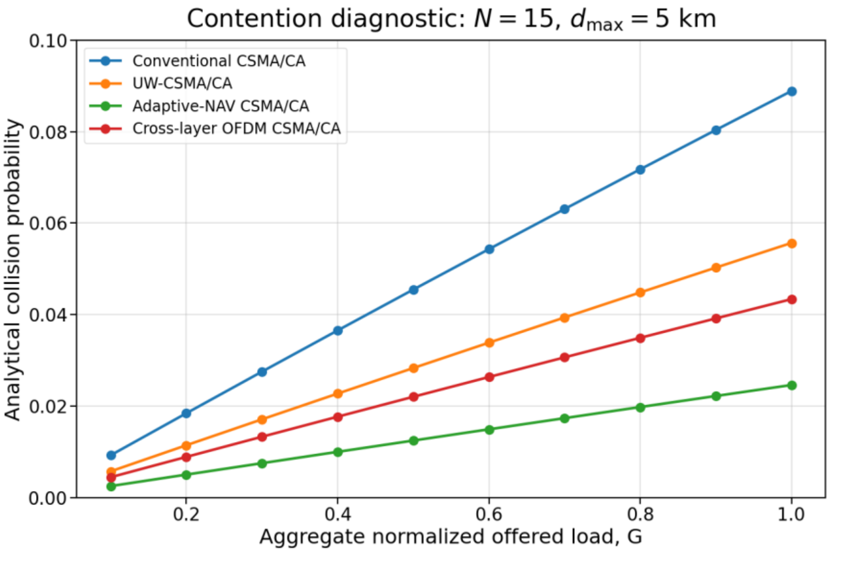

Fig. 5. Analytical collision probability versus aggregate normalized offered load (N = 15, d_{max} = 5 km).

Figure 5 shows the collision probability as the aggregate offered load Gincreases from 0.1 to 1.0, with $N = 15$and $d_{\max} = 5$km. The collision probability increases for all mechanisms as contention becomes stronger. Adaptive-NAV CSMA/CA achieves the lowest collision probability because its propagation-aware reservation better limits overlapping transmissions, which is consistent with the objective of the NAV optimisation proposed by Cho et al. (2017).

Table 2. OFDM sensitivity at N = 15, d_{max} = 5 km, and G = 0.6.

χ_{OFDM}	P_e	q_p	Throughput (kbit/s)	Delay (s)	Energy (mJ/kbit)
1.0	0.211	0.769	0.784	8.06	16,663
1.5	0.146	0.832	0.848	7.22	15,200
2.0	0.111	0.865	0.882	6.83	14,511
2.4	0.094	0.882	0.900	6.64	14,177
3.0	0.076	0.900	0.918	6.45	13,849

Figure 6 and Table 2 present the sensitivity of cross-layer OFDM CSMA/CA to the PHY-reliability factor χ_{OFDM}, with $N = 15$,

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$d_{\max} = 5\text{km}$, and $G = 0.6$. As χ_{OFDM}increases, packet success probability and throughput improve, while delay and energy consumption decrease. This behaviour is consistent with the cross-layer approach of Yin et al. (2015); however, the reliability gain is treated here as an analytical sensitivity parameter and requires BER/PER or experimental validation.

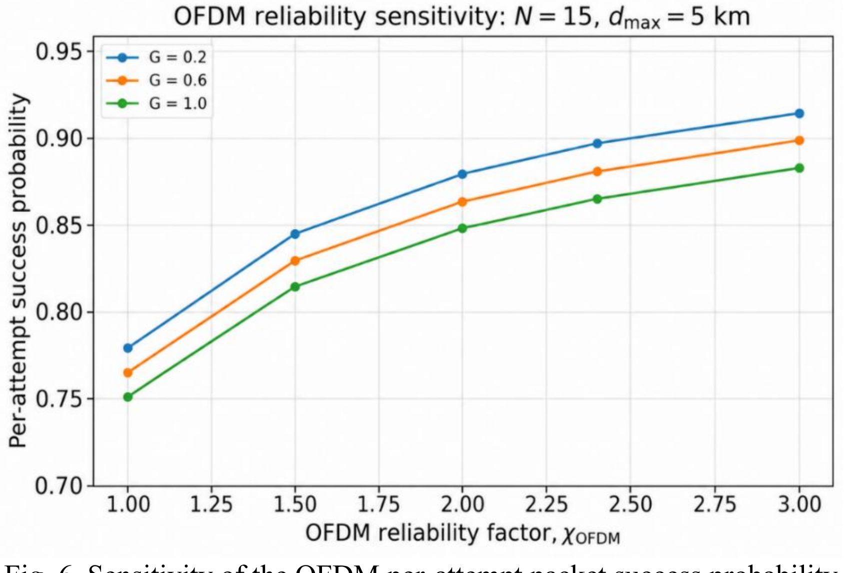

Fig. 6. Sensitivity of the OFDM per-attempt packet success probability to the assumed reliability factor (N = 15, d_{max} = 5 km).

Figure 7 compares the source-side energy cost under $d_{\max} = 5\text{km}$, $G = 0.6$, and equal PHY reliability. Adaptive-NAV CSMA/CA achieves the lowest energy cost because its lower collision probability reduces failed transmissions and retransmission-related waiting. However, the absolute energy values should be interpreted as analytical estimates because generic transmit, receive, and idle power values are used.

Based on the preceding results, Table 3 summarises the relative suitability of the evaluated mechanisms under the operating conditions considered in this study. The guidance is derived from

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the analytical trends and should not be interpreted as a universal protocol ranking.

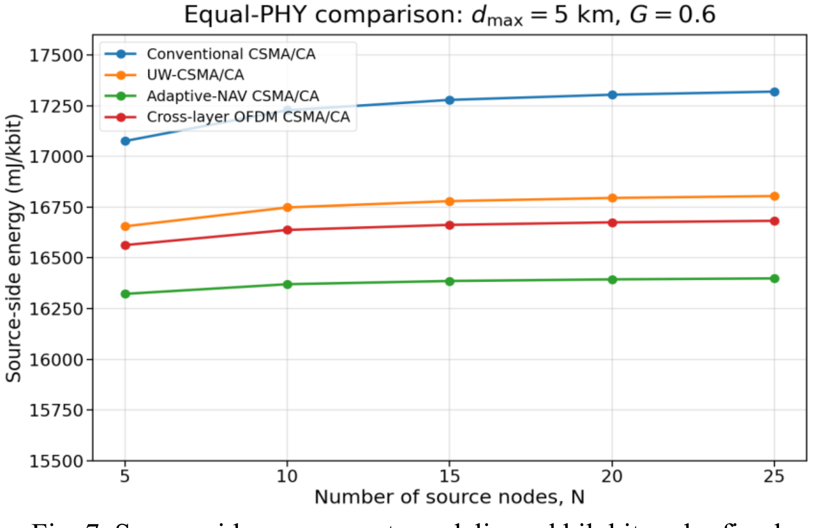

Fig. 7. Source-side energy cost per delivered kilobit under fixed aggregate load and equal PHY reliability (d_{max} = 5 km, G = 0.6).

Table 3. Protocol-selection guidance derived from the MATLAB analytical evaluation.

Operating condition	**Preferred mechanism**	**Reason**	**Important qualification**
Sparse, short-range, light load	Conventional or UW-CSMA/CA	Lowest implementation complexity	Conventional timing still needs acoustic adaptation
Long propagation with moderate contention	Adaptive-NAV CSMA/CA	Lowest collision, delay, and energy in equal-PHY model	Requires propagation-aware reservation estimates
Channel-error-dominated links with justified PHY gain	Cross-layer OFDM CSMA/CA	Reliability adaptation can offset extra overhead	Ranking depends on measured χ_OFDM
Uncertain channel and traffic regime	UW-CSMA/CA	Intermediate propagation-aware behaviour	Does not exploit full NAV or PHY adaptation

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CONCLUSION

This paper presented a propagation-delay-aware analytical comparison of conventional CSMA/CA, UW-CSMA/CA, adaptive-NAV CSMA/CA, and cross-layer OFDM CSMA/CA for a single-hop underwater acoustic star network. The equations were implemented in MATLAB to obtain reproducible numerical results. The analysis distinguishes the one-way link-level ratio, Γ_{link}, from the conservative MAC-level ratio, Γ_{MAC}. The former characterizes source-to-sink propagation severity, whereas the latter represents an upper bound on the propagation interval between spatially separated contenders and is therefore used in the collision and adaptive-reservation models. The baseline comparison used equal physical-layer reliability for all mechanisms, thereby separating MAC-level behaviour from an assumed OFDM reliability advantage.

The MATLAB results show that, under equal PHY reliability, adaptive NAV provides the best overall performance across the evaluated scenarios, achieving the highest throughput and per-attempt packet success probability and the lowest delay and source-side energy cost. The OFDM sensitivity analysis shows that cross-layer adaptation can become competitive when a defensible reliability gain is present, but its ranking remains conditional on that gain. The analytical formulation therefore provides a transparent and reproducible basis for future packet-level simulation, statistical validation, and sea-trial calibration.

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