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A Resource Efficient Encoding Algorithm for Underwater Wireless Optical Communication Link

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Abstract. The underwater communication module demands a substantial amount of power to execute its myriad functions, depleting the energy source at a rapid pace. This research work introduces a resource-optimized encoding algorithm for multi-hop communication, denoted as "resource-efficient communication", which strategically employs an optimal pulse signals for encoding sensor data generated by the underwater node. This significantly mitigates bandwidth usage during transmission, enhances payload security, consequently resulting in reduced power consumption for energy-sensitive sensor nodes. The efficacy of the resource-efficient communication algorithm is assessed by inputting various sensor data over a specific time interval. The evaluation results demonstrate a promising outcome, with a 100% run-time achievement when the sensor data exhibited gradual changes, while it still achieved a commendable 75% run-time in the case of non-deterministic variations in sensor data. The proposed algorithm accomplishes a transmission time of 100 s for steady sensor values and 127 s for fluctuating ones, using a packet size of 10,000 bytes. In contrast, the OOK modulation method requires 160 s for the same task. These results emphasize a significant enhancement in resource utilization efficiency provided by the proposed algorithm compared to conventional communication methods.

Keywords: Resource efficient Encoding · Underwater communication · Multi-hop

1 Introduction

Recent technological breakthroughs in the realm of underwater wireless communication networks (UWCN) have given birth to the emergence of the Internet of Underwater Things (IoUT) [1]. The majority of underwater communication devices rely on battery power, and replacing or recharging these batteries is a

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challenging and costly endeavor due to the harsh underwater environment. Consequently, when designing underwater wireless communication (UWC) systems, it is imperative to factor in the power consumption of underwater nodes to ensure that the network's operational lifespan can be prolonged to a practical duration [2]. Underwater wireless optical communication (UWOC) can be a viable alternative for power efficient communication [3,4]. Compared to non-return-to-zero on-off keying (NRZ-OOK) modulation, the return-to-zero OOK (RZ-OOK) modulation scheme offers the potential for greater energy efficiency in underwater optical communication (UOC). Additionally, the pulse position modulation (PPM) scheme can achieve even more significant power savings in UOC when compared to OOK. However, it's worth noting that PPM may result in lower bandwidth utilization and necessitates more complex hardware [5]. In a recent work by [6], the authors conducted a comprehensive survey on the advancements in UOC, addressing its challenges and future prospects from a layer-by-layer perspective. Their research delves into various energy-efficient routing techniques and energy harvesting methods related to UOC. This study introduces a resource-efficient encoding algorithm designed for transmitting data among multiple nodes in the field of Underwater Optical Communication (UWOC). The proposed algorithm is characterized by its requirement for less intricate hardware and a reduced pulse count for representing sensor values. Consequently, this leads to decreased power consumption and improved overall efficiency. The practical application of the proposed research is depicted in Fig. 1.

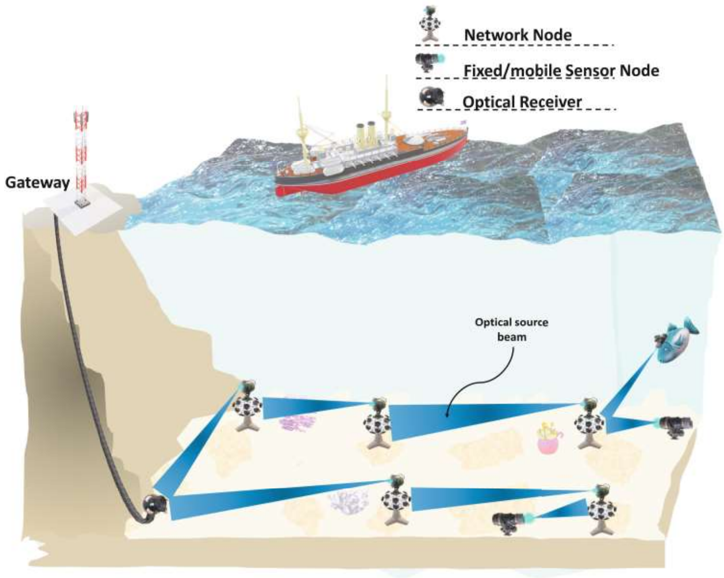


Fig. 1. Practical scenario of muti-hop UOC.

1.1 Secure Resource Efficient Encoding Algorithm

En-Coding. The algorithm commences by retrieving task-specific sensor data. Subsequently, it employs conventional communication, utilizing On-Off Keying (OOK) modulation with 8 bits per packet, for transmitting these sensor readings. Following this initial phase, the algorithm seamlessly transitions to the Channel Optimizer (CoP). The CoP, in turn, assesses the incoming sensor data by comparing it to the previous data. If this difference falls within the range of -4 to 4, the CoP activates the "Resource Efficient Communication" (REC) module within its framework. However, if the difference exceeds this threshold, the CoP continues using conventional communication (ConC) to ensure reliable data transmission.

REC. Within the Resource Efficient Communication (REC) module, the algorithm starts by determining whether the observed difference is positive or negative. A positive difference prompts REC to transmit high pulses, while a negative difference triggers the emission of low pulses. REC employs a sophisticated approach involving the transmission of four distinct combinations of dual pulses, each tailored to correspond to specific values of the observed difference. For example, when the observed difference is either $+3$ or -3, the REC module executes a transmission sequence characterized by the emission of a high pulse immediately followed by a low pulse. The REC utilizes a specific pulse pattern to convey the difference seed. It transmits two high pulses of 5 V to represent a difference seed of $+1$ or -1. Likewise, it sends two low pulses of 0 V to indicate a difference seed of $+2$ or -2. For a difference seed of $+4$ or -4, it uses a sequence of a low pulse followed by a high pulse. These pulse combinations exclusively convey the difference between the current sensor reading and the previous reading, adding an extra layer of security while also minimizing the number of pulses needed to represent the sensor data. Consequently, REC contributes to energy savings within the system and reduces transmission time. The visual representation of these intricate dual pulse combinations is thoughtfully depicted in Fig. 2. The data transmission is intended to occur over a distance of 16 m, with a total of 5 hops involved in the communication process. The pseudo code for the proposed algorithm can be found in Algorithm 1. A representation of this transmission sequence is provided in Fig. 3. In this visual representation, the white box clearly

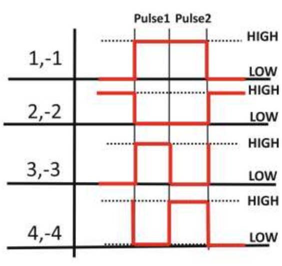


Fig. 2. Depiction of values by using combination of pulses.

signifies the activation of the REC module, whereas the dotted box distinctly marks the utilization of ConC. This innovative technique provides a significant advantage by halving the packet size, achieved through the use of four pulses, each effectively representing one byte of data. This starkly contrasts with conventional communication methods, which demand eight pulses to transmit the same amount of information. This reduction in packet size not only optimizes resource utilization but also streamlines the transmission process, showcasing the algorithm's efficiency and resource-conscious approach.

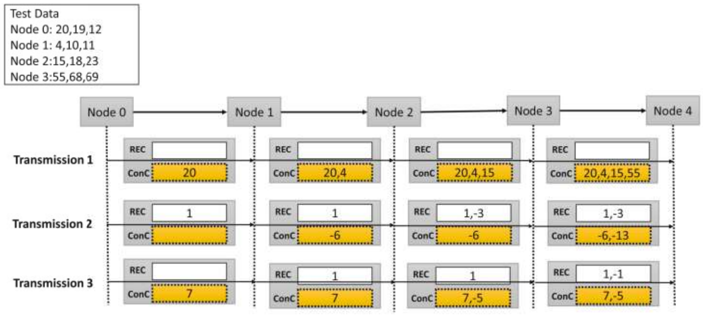


Fig. 3. Sample of transmission sequence.

De-coding. In the receiver module, the process commences with the implementation of a de-mapping algorithm. Initially, this algorithm identifies the sensor data using conventional communication demodulation techniques. Simultaneously, it monitors the communication mode employed during transmission by the Channel Optimizer (CoP) algorithm, distinguishing between ConC and REC modes. If the communication mode is ConC, the algorithm continues the reception process seamlessly by relying on conventional demodulation techniques. However, when the transmission mode is REC, the algorithm activates the REC demodulation technique. This REC demodulation unfolds through a series of meticulous steps. Initially, it determines the integer sign of the difference seed, which can be either $+1$ or -1. Subsequently, it consults a lookup table to ascertain the specific value of the difference seed. In cases with a positive integer sign and a demodulated 2-pulse value equal to 1, the algorithm proceeds to multiply $+1$ by 4. It then subtracts this product from the sensor value obtained through conventional communication. The resulting value represents the actual payload or sensor data. For comprehensive reference, the complete lookup table for other decoding processes is thoughtfully presented in Table 1. To facilitate a comprehensive understanding of the algorithm's inner workings, the pseudo-code is meticulously delineated and detailed in Algorithm 2.

Algorithm 1. Channel Optimizer, CoP

```
Require: Update SensorData
Ensure:
  NewSensorData ← Update SensorData
  Diff = NewSensorData − Update SensorData
  if Diff >= −4 AND Diff <= 4 then
    if Diff > 0 then
      FisrtPulse ← HIGH
      SecondPulse ← LOW
    else
      FirstPulse ← LOW
      SecondPulse ← HIGH
    end if
    if Diff == 1 OR Diff == −1 then
      FisrtPulse ← HIGH
      SecondPulse ← HIGH else
      if Diff == 2 OR Diff == −2 then
        FisrtPulse ← LOW
        SecondPulse ← LOW else
        if Diff == 3 OR Diff == −3 then
          FisrtPulse ← HIGH
          SecondPulse ← LOW else
          if Diff == 4 OR Diff == −4 then
            FisrtPulse ← LOW
            SecondPulse ← HIGH
          end if
        else
          Call OOK_func
        end if
      end if
    end if
  end if
```

Table 1. De-mapping Look-up Table

2-bits	Integer Sign	Sensor Value
1	+1	Sensor Data-4
1	−1	Sensor Data+4
17	+1	Sensor Data-1
17	−1	Sensor Data+1
16	+1	Sensor Data-3
16	−1	Sensor Data+3
0	+1	Sensor Data-2
0	−1	Sensor Data+2

Algorithm 2. De-Coding

Require: Update IntegerSign, LastSenseData(OOK)
Ensure:
2bits ← Update 2PulsesData
if $2bits == 1$ **AND** $IntegerSign == +ive$ **then**
$SensorData \leftarrow LastSenseData - IntegerSign \times 4$
else if $2bits == 1$ **AND** $IntegerSign == -ive$ **then**
$SensorData \leftarrow LastSenseData - IntegerSign \times 4$
else if $2bits == 17$ **AND** $IntegerSign == +ive$ **then**
$SensorData \leftarrow LastSenseData - IntegerSign \times 1$
else if $2bits == 17$ **AND** $IntegerSign == -ive$ **then**
$SensorData \leftarrow LastSenseData - IntegerSign \times 1$
else if $2bits == 16$ **AND** $IntegerSign == +ive$ **then**
$SensorData \leftarrow LastSenseData - IntegerSign \times 3$
else if $2bits == 16$ **AND** $IntegerSign == -ive$ **then**
$SensorData \leftarrow LastSenseData - IntegerSign \times 3$
else if $2bits == 0$ **AND** $IntegerSign == +ive$ **then**
$SensorData \leftarrow LastSenseData - IntegerSign \times 2$
else if $2bits == 0$ **AND** $IntegerSign == -ive$ **then**
$SensorData \leftarrow LastSenseData - IntegerSign \times 2$

end if

The flowchart encompassing all the crucial processes, including encoding, decoding, and the step-by-step execution of the REC algorithm, is visually depicted in Fig. 4.

Results and Discussions. The evaluation of the Channel Optimizer (CoP) involved inputting a variety of sensor data, with a specific emphasis on measuring the duration during which these two modules, REC, and ConC, operate within a defined time interval. It is worth noting that a longer duration for which the REC module operates corresponds to a reduced consumption of bandwidth resources by the system. These empirical findings are graphically presented in Fig. 5, which offers a detailed breakdown of the run-time percentages for various sensors under two distinct scenarios: one where the data exhibits consistent variations (St) and another where it fluctuates significantly (Fl). Specifically, the depicted run-time percentages pertain to temperature (T), humidity (H), pressure (Pre), magnetometer (Heading), and proximity (P) sensors.

These percentages are derived from the analysis of 10,000 sensor values processed by the algorithm, with each set of calculations constituting a session that is subsequently repeated in sequence. Analyzing the run-time percentages for all sensors reveals interesting trends. When sensor data shows consistent variations, REC operates at 100% of the time. This high consistency signifies significant bandwidth resource conservation during these transmissions. However, for magnetometer sensor data, which exhibits slower data variation in the form of heading measurements, the pattern is slightly different. In this case,

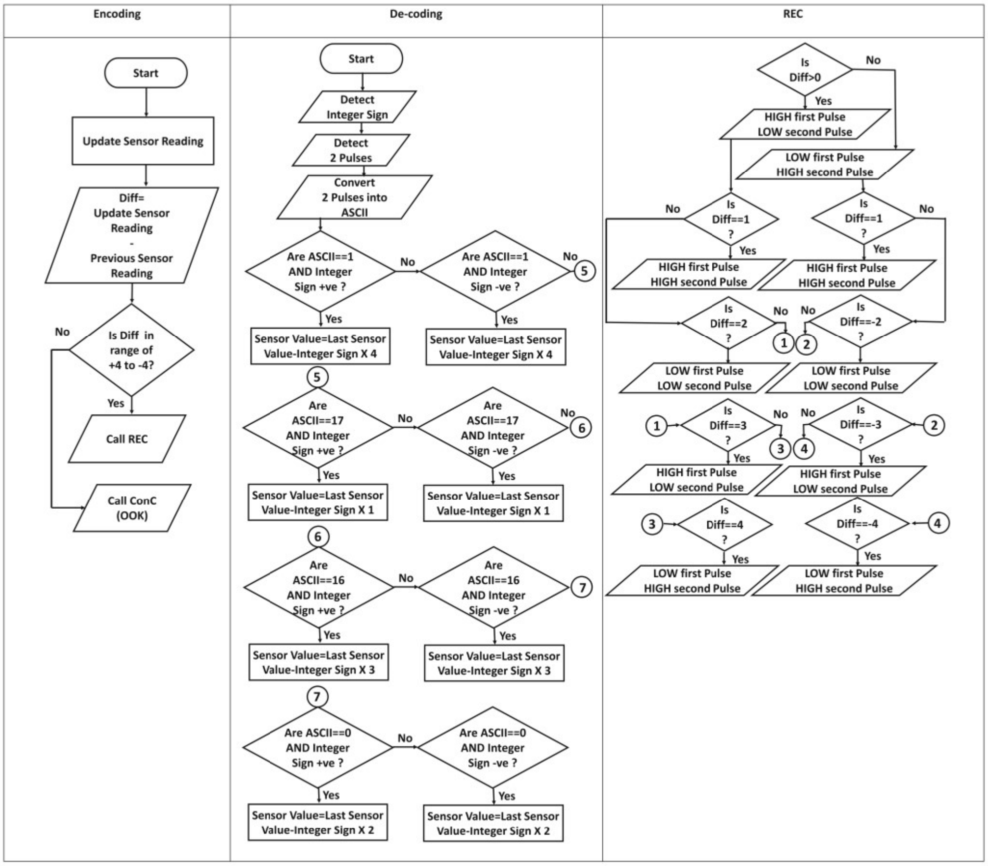
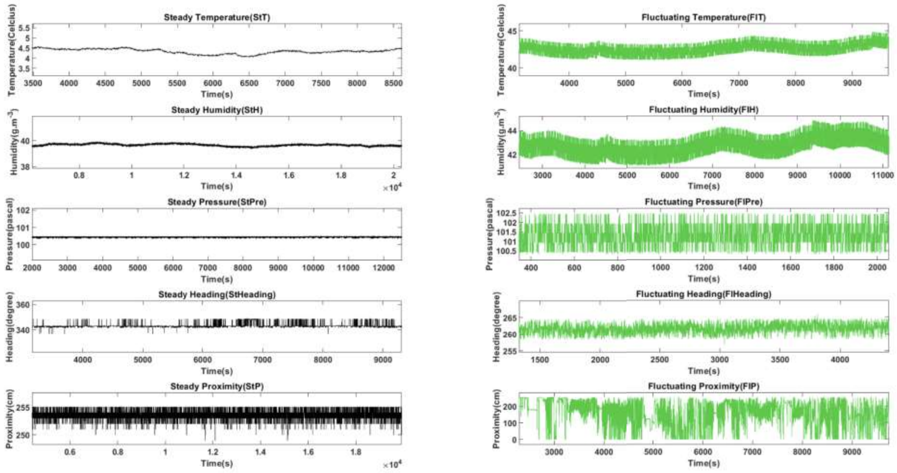
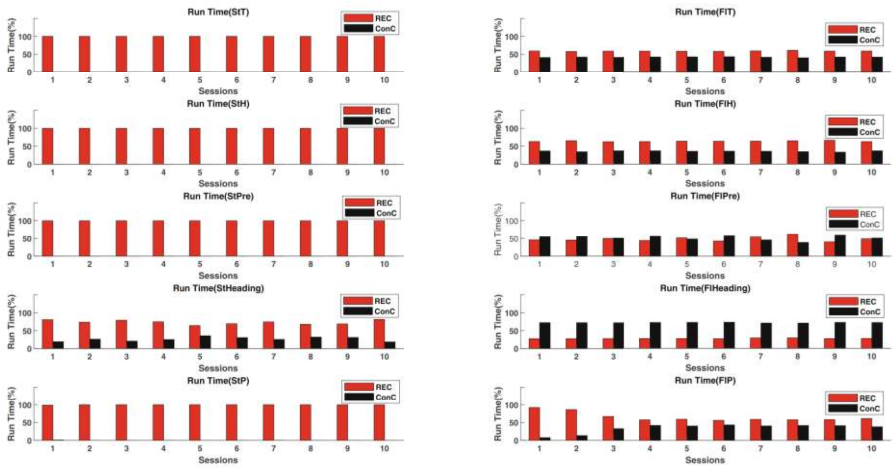


Fig. 4. Flowchart of the encoding, decoding, and the REC algorithm.

REC runs for 80% of the transmission time, with conventional communication (OOK) accounting for the remaining 20%. The evaluation also extends to situations where sensor data undergoes rapid and unpredictable fluctuations over short time intervals. In such dynamic conditions, REC and ConC exhibit varying run-time percentages. For temperature, humidity, pressure, and proximity data, the REC and ConC percentages are (60%, 40%), (60%, 40%), (50%, 50%), and (20%, 80%), respectively. In the case of magnetometer data, the percentages are (80%, 20%). These results demonstrate promising adaptability within the system, even when sensor data displays unpredictable and random fluctuations. In summary, these findings collectively offer compelling evidence of REC's ability to achieve significant bandwidth savings during the transmission process, reaffirming its effectiveness as a resource-efficient communication solution. Additionally, the transmission times for a 10,000-byte sensor payload, specifically for temperature and humidity data, are compared between the proposed algorithm and OOK modulation in Fig. 6. Specifically, for temperature data, the proposed algorithm takes 100 s to transmit a steady packet and 127 s for a fluctuating one, whereas OOK requires 160 s. Similarly, for humidity data, the proposed algorithm takes



(a) Sensor data with steady and fluctuating variance



(b) Run time percentage

Fig. 5. Run time percentage of the algorithm with different sensor data.

100 s for a steady packet and 124 s for a fluctuating one, in contrast to the 160 s needed by OOK. In summary, these outcomes collectively furnish compelling evidence of REC's ability to achieve significant bandwidth savings during the transmission process, underscoring its effectiveness as a resource-efficient communication solution. Furthermore, the system is tested in artificially induced real underwater environment. The system's performance was assessed within a water tank, involving a 4-hop communication setup where each hop had the capability to sense various environmental parameters like temperature and pressure. A blue LED (with a wavelength of 470 λ) was employed as the optical source, delivering a power of 102 mW, a luminous intensity of 2500 mcd, and a flux of 1.5 lm. To detect the optical signal at the receiver, a SiPIN photodiode was utilized,

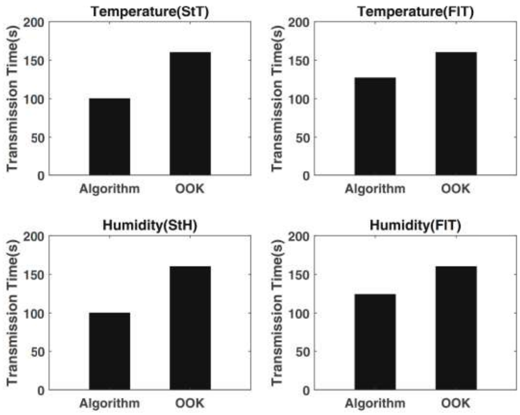


Fig. 6. Transmission time of temperature and humidity data.

featuring a photosensitive area of 10 × 10 mm^2 and a peak sensitivity wavelength of 960 nm. To replicate underwater environmental conditions, including factors like absorption and scattering, water pumps with a water displacement rate of 5 liters per minute were installed at both ends of the water tank. Additionally, small air bubbles were generated using an aerating jet equipped with two outlets, which released air at an airflow rate of 2.5 liters per minute. The ambient light levels in the surroundings were measured to range between 100–150 lux throughout the experiment. To modify the water's salinity and conductivity, and introduce fine suspended particles, the turbidity was adjusted from 0.01 to 50 NTU by introducing a solution of zinc oxide powder into the water. The experimental parameters of the underwater channel is tabulated in Table 2. The evaluation results of this experiment are presented in Fig. 7. The figure illustrates that at a communication link range of 14 m, the system attained a Packet Success Rate (PSR) of 97%, 97%, and 80% at turbidity levels of 0.09, 12, and 45 NTU, respectively. Similarly, at a link range of 16 m, the system achieved a PSR of 95%, 88%, and 73% when operating in turbid water with turbidity levels of 0.09, 12, and 45 NTU, respectively. The performance comparison of REC with other technologies, including OOK, PPM, and DPIM, is depicted in Fig. 8. The required transmission power and bandwidth values for OOK, PPM, and DPIM were sourced from a previous study [7]. The figure illustrates that REC necessitated a transmission power of 0.0005 W and 0.00067 W when the sensor readings were changing gradually (REC-St) and fluctuating rapidly (REC-Fl), respectively. This is in contrast to the required transmission power of 0.001 W, 10.47×10^{-5} watts, and 2×10^{-4} watts for OOK, PPM, and DPIM, respectively. The required bandwidth for REC-St and REC-Fl is 0.5 and 0.75 times less, respectively, compared to OOK, with the bandwidth requirement of OOK normalized to 1. In contrast, other technologies, namely PPM and DPIM, require 6.1 and 3.9 times more bandwidth than OOK, respectively. This illustrates the more efficient utilization of bandwidth by REC in both gradual and rapid sensor data variations.

Table 2. Experimental parameters used in system evaluation

Channel	Aerating Jets	Airflow rate (L/min)	2.5
		No. of outlets	2
	Water Pump (Displacement Rate (L/min))		5
	Lighting Intensity (surroundings) (lux)		100–150
	Turbidity (NTU)		0.01 to 50

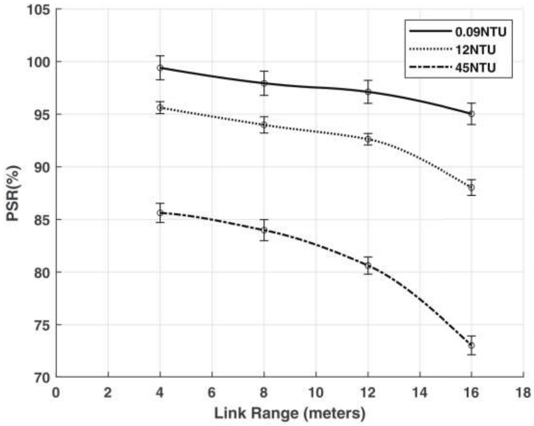


Fig. 7. Packet success rate performance in varying turbid water.

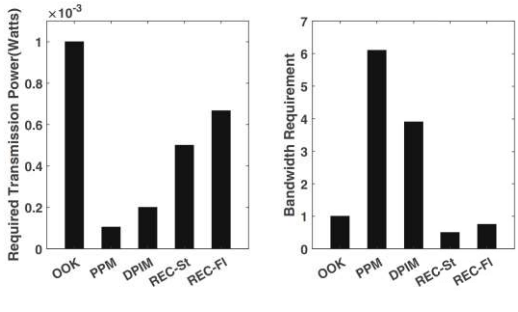


Fig. 8. Required transmission power and bandwidth comparison.

1.2 Future Implications and Applications

The careful design, coding, and evaluation of the algorithm were driven by the growing importance of energy-efficient Underwater Optical Communication (UWOC) modules in diverse settings. The algorithm is purpose-built for small mobile platform applications that demand enhanced mobility, compact design, and minimal energy consumption. It is especially well-suited for stationary network or sensor nodes used in scenarios where the monitored parameters exhibit gradual changes over time. These applications span a wide spectrum, from underwater sensor networks in aquatic research to remote monitoring systems in environmental science. The algorithm's adaptability caters to both high-mobility requirements and the stability needed for continuous data collection and transmission, making it a versatile solution for various contexts. Beyond diving communication devices and offshore fish farms, these modules can be a potential alternative in underwater environmental monitoring, oceanographic research, and marine exploration. Their non-intrusive nature ensures minimal disruption to aquatic ecosystems, and their compact size and energy efficiency make them suitable for extended deployments. Furthermore, the algorithm's optimization holds promise for future underwater communication technologies, fostering advancements in aquatic research, aquaculture management, and environmental conservation efforts.

Conclusion. In our study, we introduce a resource-efficient encoding algorithm meticulously crafted to strategically optimize resource utilization while simultaneously bolstering data frame security. The evaluation of this algorithm yields highly promising results, showcasing a substantial reduction in the number of bits required per data frame compared to conventional techniques when representing a sensor value intended for transmission.

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