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Tsunami Early Warning System Based on Maritime Wireless Communication

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ABSTRACT Tsunami buoy, linked to satellite, is commonly used as a tsunami early warning system but has been discovered to have several drawbacks such as the need for approximately 5 minutes to issue an early warning for a tsunami after detecting the initial wave as well as its fragility. It was also reported that the twenty-two buoys placed in the Indonesian seas from 2012 to 2018 were damaged and missing. Therefore, this study proposes a new method for tsunami early warning by integrating ship-to-ship maritime wireless communication. It is important to note that vessels or fishing boats with over 30 GT have the ability to travel more than 100 nmi (approximately 180 km) from the shoreline and can be equipped with point-to-multipoint VHF radio communication. Meanwhile, smaller boats on the fishing ground located approximately 2-5 km from the shore can use a WiFi network to communicate like a wireless mesh while the existing terrestrial network can be used for the ship-to-shore communication between boats and land stations. This system is expected to provide significant benefits for a fishing town such as Pangandaran, West Java, Indonesia which is directly facing Java Megathrust in the Indian Ocean. Therefore, a tsunami numerical simulation was conducted in this study using Shallow Water Equation which involved a hypothetical tsunami simulated from the possible fault source which is approximately 250 km from the source. Moreover, the vessel's location was assumed to be in line with the fishing ground while the arrival time of the tsunami was estimated from the model to be 22.5 minutes and compared to the relay time of the proposed system which was approximately 5.4 seconds. This is faster in terms of delay than the existing system which relays information through satellite at approximately 5 minutes in an ideal condition and also has the ability to reduce the need for tsunami buoys.

KEYWORDS Tsunami modeling; Tsunami propagation; Maritime wireless communication; Early warning system; Shallow water equation.

1 INTRODUCTION

Tsunami waves have the ability to cause significant damage to coastal areas; and countries which are located in the so-called "Ring of Fire" has a high tsunami risk. This is observed from past incidents such as The Great Indian Ocean Tsunami 2004, The Great North East Japan Tsunami 2011, and The Sulawesi Tsunami 2018 with massive destruction on the affected coastal area. Moreover, tsunamis have caused more than 470,000 deaths worldwide in the past 450 years with the 2004 Great Indian Ocean Tsunami reported to have caused 230,000 casualties (Lavigne et al., 2007).

An M7.8 earthquake occurred at a depth of 10 km off the coast of Pangandaran, Central Java, Indonesia on 17 July 2006 and triggered a deadly tsunami of average 3–8 m which inundated the southern coastal area of Java (Hanifa et al., 2009;

Kongko and Schlurmann, 2010). This led to the classification of the earthquake as a destructive and tsunami-earthquake. It was reported that approximately 668 people died, 65 were missing, and 9,299 were injured (Lavigne et al., 2007).

Most tsunamis originate from a seismic displacement of the seafloor (Andrade et al., 2006). It has also been discovered that earthquakes that occur in the middle of the sea with less than 30 km depth and more than 6.5 Mw strength have the ability to generate tsunami waves (Subardjo et al., n.d.). Therefore, several Tsunami Early Warning Systems (TEWSs) usually rely on seismic-based monitoring of tsunamigenic sources. For example, Indonesia Tsunami Early Warning System (InaTEWS) normally sends the information 5 minutes after the earthquake through SMS, social media, email, fax, website, WRS, and GTS. This system needs regular maintenance due to the fact that it relies on monitoring buoys and twenty-two buoys were reported to have been damaged and missing from 2012 to 2018 in Indonesian seas (Fathiyah Wardah, 2018; Sutrisno Eri, 2021). This indicates the country desperately needs a faster and more reliable backup system which can work with TEWS to issue a more effective initial warning. Several efforts have been made to upgrade and expand the world's tsunami warning systems since the 2004 Indian Ocean tsunami such as those directed towards improving the spatial distributions of DART, buoys, and coastal tide gauges as well as ensuring better seismological and tsunami modeling capabilities (Jin and Lin, 2011), (Emile A. Okal, 2006). Moreover, the master plan of the Indonesia Maritime Communication System which is known as Maritime Wireless Communication (MWC) is also considered important in developing a new scheme of tsunami early warning systems in the country.

This MWC which was arranged by International Telecommunication Union (ITU) is an integration of satellite, ship-to-ship, and ship-to-shore communication systems. According to Jiang (2019), it consists of the maritime radio system, mobile communication system, wireless ad hoc network, high altitude platform, satellite, and cable underwater system. It is important to note that satellite communications are commonly used to transmit high data-rate maritime information services such as the data from buoys as tsunami early warning system, however, the data transfer cost is approximately 30 times more expensive considering the fact that approximately $300–2000 is usually expended on satellite per month (Yau et al., 2019). The maritime radio system is the most popular and mature communication system developed mainly for ship-to-ship and it is usually based on the legacy of Ultra High Frequency (UHF) and Very High Frequency (VHF). Meanwhile, radio communication can only support basic applications and services such as voice, text messaging, email, and web surfing (Ta et al., 2011). This current research only focuses on ship-to-shore communication using WiFi technology which was selected due to its capability to transmit high-rate data with a suitable coverage area for ship-to-shore communication.

A previous study on the application of VHF radio waves to maritime communication systems discussed Non-Contiguous OFDM (NC-OFDM) transceiver design for maritime cognitive radio (CR) in the range of 156.3625 – 156.8875 MHz (Wael et al., 2018). The CR was observed to be beneficial because it can interoperate with other communication systems by adjusting its waveform, allocating its resources in the best way, and choosing a suitable transmission channel. Meanwhile, NC-OFDM is one of the CR techniques which enables Dynamic Spectrum Access (DSA) and this simply means it is a conventional OFDM with a mask to activate or deactivate its subcarriers in order to mitigate the interference. There has been further analysis on the effect of performance channel on NC-OFDM technique based on sea condition data of the Java Sea and Karimata Strait. The Douglas Sea scale 4 with a moderate wave height of 1.25 m – 2.50 m was simulated and the Bit Error Rate (BER) was estimated to be 10-2 (Mitayani et al., 2019). Furthermore, comprehensive research regarding the utilization of WiFi 5 for maritime communication services was presented in Mitayani et al. (2020) after which the path loss model of several channel conditions in Indonesia seas was simulated and the results showed that the 3-ray model is considered the best model to estimate the path loss t in the maritime channel of the seas. This present research focuses on assessing the concept of a tsunami early warning system based on maritime wireless communication in Indonesian seas. This is associated with the expectation of MWC to deliver tsunami warnings faster and more reliable compared to the seismic-based floating buoys which use satellite communication. The objective was to determine the speed and reliability of the MWC -based tsunami early warning system which is ideally better than buoys.

2 METHODS

A hypothetical tsunami was simulated using Shallow Water Equations (SWE) as shown in Equations 1 and 2 from the possible fault source which is approximately 250 km from the source. This SWE has been widely used to simulate tsunami wave propagation (Yakti et al., 2018; Adityawan and Tanaka, 2012; Synolakis, 1987).

$$\frac{\partial h}{\partial t}+\frac{\partial (Uh)}{\partial x}=0 \qquad (1)$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+g\frac{\partial (h+z_b)}{\partial x}+\frac{\tau_0}{\rho h}=0 \qquad (2)$$

where h is the water depth (m), U is the depth-averaged velocity (m/s), t is the time (s), τ_0 is the bed stress (N/m^2), and is the fluid density (kg/m^3). The bed stress was assessed using the Manning equation based on the assumption that the bed stress relation in the conventional Manning method is proportional to the square of the velocity Adityawan and Tanaka (2012) as shown in the Equation 3.

$$\frac{\tau_0}{\rho}=g\times n^2\times\frac{U|U|}{R_h^{(1/3)}} \qquad (3)$$

Where τ_0 is the bed stress (N/m^2), is the fluid density (kg/m^3), g is the acceleration of gravity (m/s^3), n is the Manning roughness, U is the depth-averaged velocity (m/s), and R$_h^{(1/3)}$ is the hydraulic radius or water depth for a very wide channel (m). Moreover, the solitary wave equation was used to model the initial profile and velocity of the solitary wave Synolakis (1987) while the wavelength was obtained using Equation 4.

$$L=\frac{2}{\sqrt{\frac{3H}{4h_0^3}}}\left[arccosh\left(\sqrt{\frac{1}{0.05}}\right)\right] \qquad (4)$$

Where L is the wavelength (m), H is the initial wave (m), and h_0 is the water depth (m). The wavelength obtained was later used to calculate the initial wave peak (X_1) which is situated at half of the initial wavelength ($\frac{L}{2}$) from the initial slope (X_0). Moreover, the initial profile and velocity of the solitary wave were calculated as shown in Equations 5 to 7:

$$\eta(x,0)=H\times sech^2\left(\sqrt{\frac{3H}{4h_0^3}}(x-X_1)\right) \qquad (5)$$

Where is the initial profile of solitary wave (m), H is the initial wave (m), h_0 is the water depth (m), and X_1 is the half of the initial wavelength (m).

$$c=\sqrt{g(H+h_0)} \qquad (6)$$

Where c is the celerity (m/s), g is the acceleration of gravity (m/s^2), H is the initial wave (m), and h_0 is the water depth (m).

$$U(x,0)=\frac{cH}{1+\eta} \qquad (7)$$

Where U is the initial velocity of solitary wave (m/s), c is the celerity (m/s), H is the initial wave (m), and η is the initial profile of solitary wave (m). It is important to note that MacCormack's finite difference predictor-corrector scheme was used to solve the governing equation with the predictor step conducted using a forward difference in space and time while the corrector step was through a backward difference in space and a forward difference in time. The final value was obtained using a center difference in time from the initial and the corrector value (Adityawan and Tanaka, 2012). The model also adopted a numerical filter for water depth and velocity as proposed by Hansen (1962) to act as an artificial dissipation for better stability in the calculation. Moreover, a wet-dry boundary condition was applied in the model to allow run-up simulation with the smallest threshold depth selected, hence, when the water depth calculated is lower than the threshold, it means the water depth and velocity in the corresponding grid are equal to zero value (dry cell) (Adityawan and Tanaka, 2012).

The hypothetical tsunami used in this study was simulated based on the Pangandaran 2006 Tsunami Event Rikarda et al. (2020) which was selected due to the fact that Pangandaran is popular for its fisheries. A fishing ground is located approximately 5 km from its shoreline and bigger fishing vessels are allowed to travel further up to 200 km from the shoreline, thereby, indicating the suitability of the maritime early warning system in the area.

The model was developed using the SWE and solitary wave equation while the arrival time from the tsunami was simulated using MatLab. Moreover, an initial solitary wave with a wave height (H) of 4 m was propagated along the sea with frictionless conditions in the deep sea and Mannings roughness (n) of 0.025 in the shallow sea at 10 m depth. The initial wave height was also located 170 km from the shoreline while the seabed level was at -1,000 m and the shoreline was assumed to have a uniform slope of 0.03. The model scheme is shown in Figure 1.

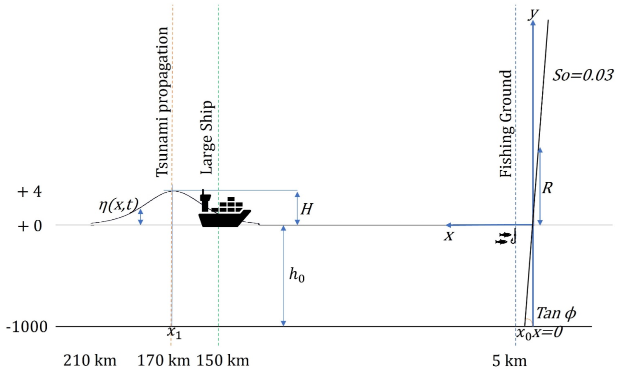

Figure 1 Pangandaran hypothetical tsunami model scheme

The early warning system was developed by integrating ship-to-ship and ship-to-shore maritime wireless communication as shown in Figure 2. It is important to note that vessels or fishing boats with over 30 GT can travel more than 100 nmi (approximately 180 km) from the shoreline and were equipped with point-to-multipoint VHF radio communication. Meanwhile, the smaller boats on the fishing ground located approximately 2-5 km from the shore used a 5 GHz WiFi network to communicate like a wireless mesh and the ship-to-shore communication between boats and land stations used existing terrestrial or WiFi network.

First, the signal propagation time in the open sea area which is located around 5-180 km (175 km) from the shoreline was calculated. It is important to note that the fishing boats used are 30GT and 100GT boats with 2.0 m and 3.6 m heights respectively plus an additional 4.0 m pole height for the total antenna. Moreover, the formula from Mitayani et al. (2020) was used to calculate total workable distance antenna coverage based on the antenna height while the total workable distance per kilometer was adjusted by reducing 20% of the total distance to accommodate the weather condition, wave, and other losses. It was possible to obtain the total hops for 175 km distance open sea area after which the signal propagation delay was calculated with the formula from Haug (2019) and a one-way delay of 2.18 ms multiplied by the number of hops was added (Mehraban and Ghahyazi, 2012) to determine the total delay for VHF communication on open sea area. Second, the signal propagation time for fishing ground located 5-0 km from the shoreline was also calculated using the WiFi mesh network assumed to be installed on small fishing boats. It is pertinent to note that an experiment has already been conducted to determine the optimum distance per hop for WiFi mesh network and the WiFi transfer data speed was observed to be declining after 180 m as shown in Figure 3 and Table 1. This analogy was used to obtain the maximum distance for WiFi network coverage per-hop which was 250 m and this was followed by the calculation of the total hop for the WiFi networks based on the WiFi network coverage.

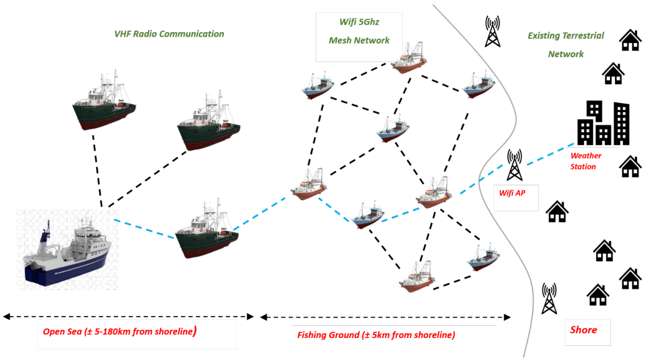

Figure 2 Tsunami early warning system based on MWC system

The data from Mehraban & Ghahyazi (2018) was used to calculate the one-way delay using the formula y = 2.8090x - 0.2442, where y is delay (ms) and x is the hop count as shown in the Figure 4. The same formula was also applied to determine the signal propagation time from the shoreline to the weather station which is assumed to be located 1 km from the shoreline. Lastly, the waiting time parameter which was set at 5340 ms was added to the UDP data transfer for the 2048 Kbps rate and

Figure 3 Wifi coverage experiment on the Fishing Ground

Table 1. Throughput UDP test on the Fishing Ground

Interval (s)	Transfer (Mbytes/s)	Bandwidth(Mbits/s)	Jitter(ms)	Lost/Total Datagram
0.0 – 12.4	2.37	2	4.16	11/1702
	835K	566K	67.74	170/752
	698K	462K	317.37	155/641
	2.94	2.57	2.63	29/2,127
	2.98	2.5	0.98	0/2,127
	2.05	1.51	80.8	33/1,493
	3.58	3.01	1.03	0/2,552
	3.43	2.77	13.84	44/2,490
	4.17	3.5	1.21	0/2,978
	4.39	3.58	9.74	9/3,142
	2.96	2.42	10.05	73/2,184
	4.53	3.8	0.17	0/3,233

1400 Bytes payload.

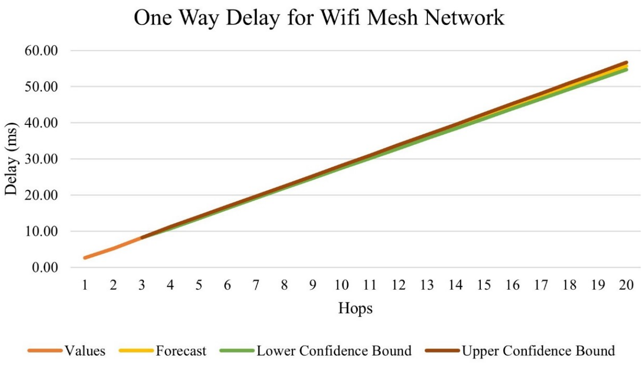

Figure 4 One way delay for WiFi mesh network

Vessels or small boats were assumed to be in a line-of-sight position per-hop while the arrival time of the tsunami was estimated from the model and compared to the signal propagation time of the proposed system. The propagation time was limited only from the farthest vessel which was at 170 km to the weather station onshore.

3 RESULT

The arrival time of the tsunami wave was estimated from the model as shown in Figures 5 and 6, and the initial wave peak was generated at 170 km from the shorelines. The peak was observed to have arrived at 150 km from the shoreline in 3.3 minutes and propagated to the shoreline. The tsunami also arrived at 5 km from the coastline which is the fishing ground in 21.7 minutes and at the coastline in 22.5 minutes as shown in Figure 6, and later receded after 35 minutes from the initial generation.

The parameters of the MWC used by the proposed early warning system are presented in Table 2. Meanwhile, the signal propagation time was calculated for 2 simulations which involved the situation where the tsunami occurs from the open sea at 210 km and the fishing ground at 5 km. It is important to note that the simulation was conducted based on the best and worst conditions. The best condition assumes that all vessels are 100 GT and equipped with a 10 m antenna from sea level which allows communication on a longer distance while the worst condition assumes that all vessels are 30 GT and equipped with 4 m antenna from sea level which allows communication only on a shorter distance. The calculations are presented in Tables 3, 4, and 5 while the results are shown in Tables 6 and 7.

Table 2. MWC Parameter

Parameter	
VHF Freq	156.8 Mhz
Wifi Freq	5 GHz
Payload	1400 Bytes
Data Rate	2048 Kbps
Antenna Height 1 (30GT Boat)	6 m (worst scenario)
Antenna Height 2 (100GT Boat)	10 m (best scenario)
Wifi Hop Distance 1	150 m (worst scenario)
Wifi Hop Distance 2	250 m (best scenario)
One Way Delay per Hop	2.18 ms

4 DISCUSSION

Several limitations are associated with this research such as the assumption that necessary tools are installed in the ships at the sea to transmit information from the ship closest to the tsunami center to the one near the weather station, the distance between these ships is within the maximum range of the antenna, lack of detailed measurements which led to the use of the basic formula, failure to calculate the delay for each device, and the failure to use the actual bathymetric data influencing the wave deformation and energy dissipation during tsunami propagation in the tsunami arrival time approach. Meanwhile, the assumption of an ideal condition showed that the signal propagation time to relay tsunami early warning data from open sea to weather station office is 5.48 s for the worst scenario and 5.42 s for the best scenario. It was also discovered that the signal propagation time when the tsunami occurs in the fishing ground is 5.45 s for the worst condition and 5.40 s for the best scenario.

The tsunami early warning system was divided into three parts which include T1 when the earthquake happened, T2 when the tsunami was gen-

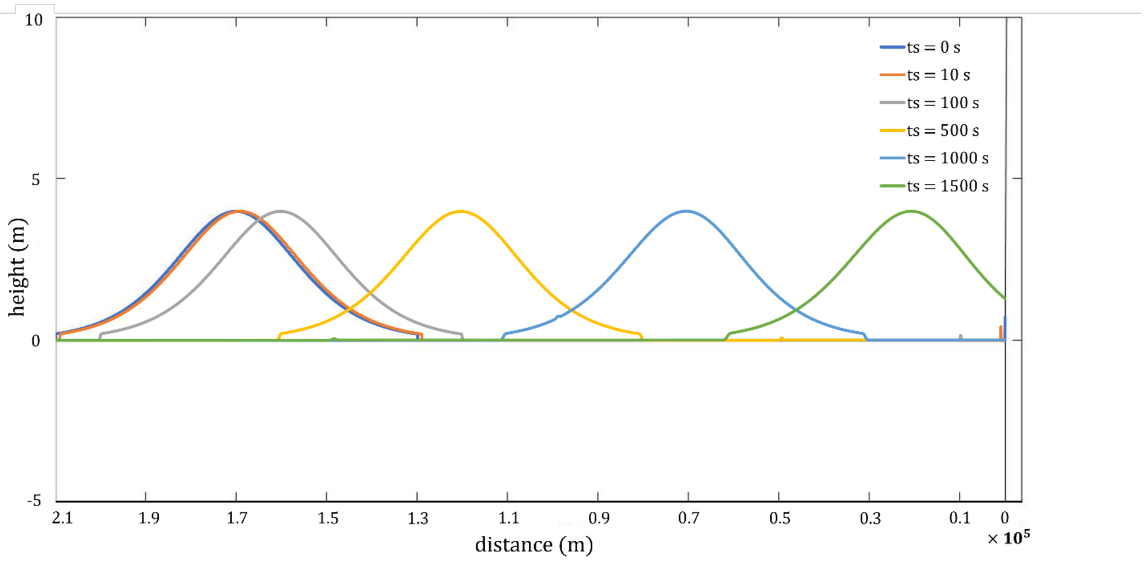

Figure 5 Pangandaran hypothetical tsunami propagation

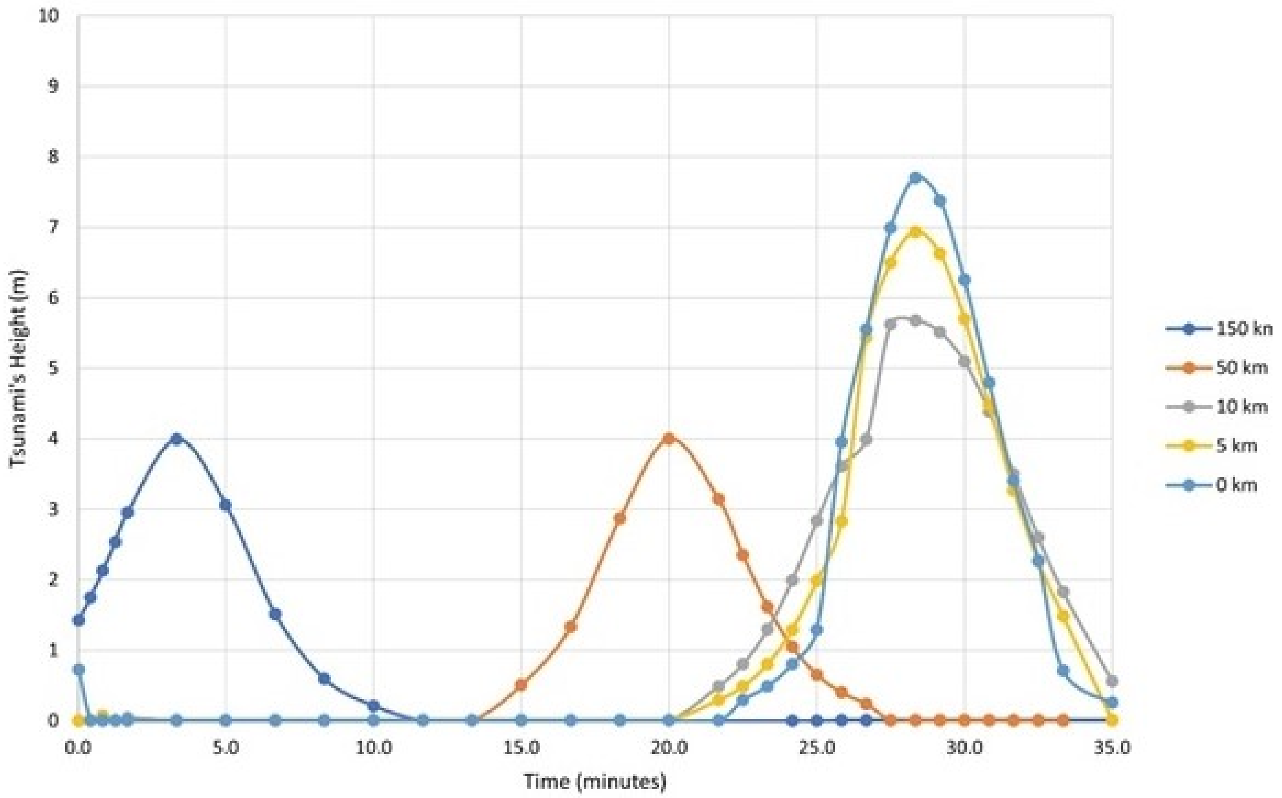

Figure 6 Tsunami water level

Table 3. Total one-way delay calculation at Open Sea

Scenario	Near End		Far End		Total Workable Distance (km) per HOP	Adjusted Total Workable Distance (km) per HOP	Total HOP VHF	Propagation Delay VHF (ms)	Total One Way Delay all HOPs (ms)	Propagation Time VHF (ms)
	Antenna Height (m)	Coverage (km)	Antenna Height (m)	Coverage (km)						
Worst	6	8.76	6	8.76	17.53	14.02	13	0.58	28.38	28.96
Best	10	11.31	10	11.31	22.63	18.1	10	0.58	21.1	21.68

Table 4. Total one-way delay calculation at Fishing Ground

Scenario	Total Workable Distance (km) per HOP*	Total HOP WiFi	Total One Way Delay all HOPs (ms)**
Worst	0.15	33	93.39
Best	0.25	20	55.93

erated, and T3 when the evacuation process is required before the tsunami inundation. It is important to note that InaTEWS/buoys require 5 minutes from the detected earthquake or seismic displacement to provide the early warning while MWC only requires approximately 5 seconds to relay the information from the sea to the ground.

The tsunami early warning can be received by approximately 5.5 seconds assuming the initial wave

Table 5. Total one-way delay calculation at Shoreline-Weather Station (1 km)

Scenario	Total Workable Distance (km) per HOP*	Total HOP WiFi	Total One Way Delay all HOPs (ms)**
Worst	0.15	7	18.48
Best	0.25	4	10.99

Table 6. Tsunami occur at Open Sea (170 km from the shoreline)

Scenario	Propagation Time (ms)				Total Propagation Time (s)
	Open Sea-VHF	Fishing Ground-WiFi	Shore-WiFi	Waiting Time	
Worst	28.96	93.38	18.48	5,430	5.48
Best	21.68	55.93	10.99	5,340	5.42

Table 7. Tsunami occur at Fishing Ground (5km from the shoreline)

Scenario	Propagation Time (ms)			Total Propagation Time (s)
	Fishing Ground-WiFi	Shore-WiFi	Waiting Time	
Worst	93.38	18.48	5,340	5.45
Best	55.93	10.99	5,340	5.4

is recorded by a vessel on the open sea which is a lot faster than the 5 minutes estimated to be required by the buoy system. It is important to note that the tsunami is expected to arrive at the shoreline within 22.5 minutes. However, the wave is detected by any vessel in the fishing ground when there is no vessel on the open sea and the warning is sent within 5.4 seconds while the wave reaches the shoreline within 1 minute from the fishing ground.

5 CONCLUSIONS

This research studied the tsunami early warning system design based on maritime wireless communication by simulating a hypothetical tsunami which resembles the Pangandaran Tsunami of 2006 using the SWE model. The tsunami wave was estimated using the solitary wave equation and its results were used to determine the tsunami travel time. It was discovered that the tsunami arrived at the 5 km from the coastline in 21.7 minutes and at the coastline in 22.5 minutes.

The system was developed based on ship-to-shore maritime wireless communication with the relay time estimated using the data collected from previous studies and multi-hop wireless communication model to be 5.4 seconds. This is faster than the 5 minutes estimated for the existing system which relays information through satellite and also does not require any buoys. However, there is a need to study the performance of this proposed early warning system further before its implementation as part of the tsunami mitigation plan.

DISCLAIMER

The authors declare no conflict of interest.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the author.

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