Efficiency of AX.25 Protocol in a Wireless SCADA Communication System for Monitoring Performance of Micro-Hydro Power Plants

Salahuddin¹, Bakhtiar², Yusman³, Fadhli⁴
TeknikElektroPoliteknikNegeriLhokseumawe
Email: salahuddin.mt@pnl.ac.id; bakhtiar@pnl.ac.id; yusman@pnl.ac.id; fadhli@pnl.ac.id

Abstract. This paper presents the results of testing and estimating the efficiency of the AX.25 protocol implemented in the wireless SCADA communication system for monitoring the performance of the Micro-hydro Power Plant (MHPP). This protocol is commonly used for packet radio communications. AX.25 is a layer 2 protocol (referring to the OSI layer reference), the Data Link Layer. As a layer 2 protocol, AX.25 is responsible for building link connections, providing logic procedures for transferring connections and disconnection. This system can monitor several MHPP parameters such as voltage, current, frequency, and turbine rotation and can be accessed directly at one centralized location. Data from sensors installed in the generator are converted into digital data on the microcontroller contained in the Remote Terminal Unit (RTU). This data is then sent to the Main Terminal unit (MTU) so that it can be a reference for operators to decide further if there are MHPP parameters that change from the predetermined standard. AX.25 protocol is implemented on an arduino microcontroller hardware that functions as a Terminal Node Controller (TNC) that will regulate the traffic of data communication between several RTUs and MTU. In accordance with RTU requests, TNC will forward the data sent by the RTU with certain "call signs" to be forwarded to MTU and displayed at the monitoring center. The test results show that the efficiency of AX.25 protocol at transmission rates of 1.2 kbps, 2.4 kbps, 4.8 kbps and 9.6 kbps tends to be linear with respect to changes in delivery start-up time and does not have a significant impact on changes in start-up time transmitter. For all given k values, when T103 = 5, regardless of transmission rate, the protocol can achieve an efficiency of around 90%.

Keywords: System implementation, wireless SCADA communication network, Terminal Node Controller, Remote Terminal Unit, Main Terminal Unit, AX.25 Protocol, MHPP.

1. Introduction
The AX.25 protocol is a modification of the X.25 protocol specifically used by amateur radio. This protocol is commonly used for packet radio communications. In the physical layer, this protocol uses Bell 202 AFSK modulation standard (Audio Frequency Shift Keying). AFSK modulation is different from FSK modulation. In FSK modulation, FSK binary numbers will immediately change the carrier frequency. Whereas the AFSK signal is converted in the form of an audio signal, ie at a frequency of 1200Hz for the mark and 2200Hz for space. The use of this AFSK modulation is used to make it easier when connected with a transceiver device that has been made in the form of HT, so that it only connects the required sound
line. The audio signal from the AFSK that will modulate the carrier signal, usually by the frequency modulation (FM) method.

MHPP is a small-scale power plant that uses hydropower as a driving force whose sources such as irrigation canals, rivers or natural waterfalls by utilizing the head height and the amount of water discharge. Technically, MHPP has three main components, namely water (as an energy source), turbines and generators. The MHP gets energy from a stream of water that has a certain height difference. So far, monitoring the performance of MHPP parameters is carried out directly at the plant's location. This study aims to build a system for monitoring MHPP wirelessly by utilizing the AX.25 protocol. The system developed is expected to monitor several MHPP parameters such as frequency, voltage, current and rotation of the turbine and at one centralized location.

Some of the problems found in developing a system for monitoring the performance of MHPP wirelessly include how the system is implemented online, how microcontrollers convert sensor-readable data, how TNC manages data transmission from several RTUs, and how to build a wireless SCADA system based on the AX protocol. 25 for centralized monitoring of Micro hydro power plants.

2. Literature Review

2.1. AX.25 protocol
The AX.25 protocol is a modification of the X.25 protocol specifically used by amateur radio. This protocol is commonly used for packet radio communications. In the physical layer, this protocol uses Bell 202 AFSK modulation standard (Audio Frequency Shift Keying). The use of this AFSK modulation is to make it easier when connected with a transceiver device that has been made in the form of HT, so that it only connects the required sound line. The audio signal from the AFSK that will modulate the carrier signal, usually by the frequency modulation (FM) method.

Protocol AX25 (Amateur X.25) is a special protocol used by amateur radio which is the development of the X.25 protocol. In the OSI (Open System Interconnection) communication model, this protocol plays a role in managing communication at layer 1 (Physical) and layer 2 (Data Link). Radio packet transmission in the Link Layer is sent in small blocks of data called frames. There are several types of frames / packages in the AX.25 protocol, but only the Frame Information (UI) used in APRS. The UI Frame is transmitted scattered to all existing recipients, and there is no acknowledgment process, even if a packet is not received, the packet is not resent. This is not a problem, because in APRS there is periodic data packet transmission.

2.2. TNC (Terminal Node Controller)
The TNC is a microprocessor-based device that is often used in data communication on amateur radio packet networks. The main function of TNC is to establish a connection between the RF Transceiver and a computer that functions as a DTE (Data Terminal Equipment) device such as a PLC or weather station [9]. Computers act only as consoles only and thus must be equipped with terminal emulation software. The TNC function consists of the assembly and dismantling of the frame and modulation and demodulation to adjust the data format transmitted through the computer's serial port according to the requirements of the wireless transmission line[10].

The TNC hardware structure consists of digital and analog parts. The digital part is a typical microprocessor system with two serial ports and memory and data programs. The memory section is used to support information that is sent and storage of controller parameters. The analog part contains a modem that allows connection with the RF transceiver. The TNC hardware structure is shown in Figure 1.
2.3. Microhydro Power Plant (MHPP)
MHPP in principle utilizes the height difference and the amount of water discharge per second that is in the flow of irrigation canals, rivers or waterfalls. This water flow will rotate the turbine shaft to produce mechanical energy[4]. This energy then moves the generator and generates electricity. The MHP illustration can be seen in Figure 2.

The construction of the MHPP needs to begin with the construction of a dam to regulate the flow of water that will be used as propulsion of MHPP [7]. Dams need to be equipped with sluice gates and garbage filters to prevent the entry of dirt or silt. Near the dam built intake building. Then proceed with the manufacture of a conduit that serves to drain water from the intake. At the end of the overflow channel, a settling pond was built. This pool functions to settle sand and filter dirt so that the water that enters the turbine is relatively clean. This channel is made with concrete construction and is as close as possible to the turbine house to save fast pipes. Rapid pipes function to drain water before entering the turbine. Usually made of steel pipes that are pulverized, then welded. Flanges are used for connection between pipes.
2.4. SCADA
SCADA is a system that collects data from various sensors at a factory, plant or in another remote location and then sends this data to a central computer which then manages and controls the data. Initially, SCADA was designed to be on a private network that uses communication lines. Because of the greater scope of its use, the use of this communication line has become impractical, because it introduced an integrated wireless communication system for SCADA[2]. In particular, the SCADA system includes several parts including, operating equipment such as pumps, valves, conveyors and branch breakers that can be controlled by actuators or relays. Instruments in the field or in facilities that are sensitive to conditions such as pH, temperature, pressure, power level, and flow rate. Then a close communication network between local processors and instruments and operating equipment. This section includes a Programmable Logic Controller (PLC), Remote Terminal Unit (RTU), Intelligent Electronic Devices (IED) and Process Automation Controller (PAC)[1][6].

![Figure 3. Typical wireless SCADA system](image)

3. Research Methods

3.1. Determination of the AX.25 protocol parameters
The characteristics of the AX.25 and TNC protocols can be set with a large number of parameters. Some of the following are important parameters seen from the perspective of protocol efficiency, namely:

- \( k \), the maximum number of frames sent in sequence before waiting for the acknowledge process (window size).
- \( N1 \), the maximum capacity of the data field in a U or I frame, less than 256 bytes.
- \( T2 \), the time spent between the acknowledgment process and the end of the frame.
- \( T102 \), the duration of collision avoidance slots, ranges from 50 ms to 300 ms.
- \( T103 \), the time for stabilizing the transmitter parameters after starting the transmission and for the detection of the carrier in the receiver. Depending on the RF capability of the transceiver and usually varies between tens to hundreds of milliseconds.
- \( p \), persistence parameter, the transmission probability is usually 25% of the maximum value of frame capacity 256 which means equal to 64.

3.2. System Performance Standards
The AX.25 protocol can operate in half-duplex or full-duplex connection mode [5]. In these two methods, before the transmission starts, the station must check whether the channel to be targeted is free or ready to receive transmission data. This process is carried out with a \( p \)-persistent carrier sense mechanism. With a variety of \( p \) and \( T102 \) values given, the average delay time for medium access is calculated as follows:

\[
T_{CS} = \frac{256T_{102}}{2(p+1)}
\]
With,
\( T_{CS} \) = average time delay for medium access
\( T_{102} \) = duration of collision avoidance slots (collision avoidance)

After that, the transmitter is turned on. Then, the sender waits until \( T_{103} \) to ensure that the transmitter works stably and sends the information frame (I). In the case of a half-duplex connection, if the window size \( (k) \) is greater than one and the frame is sufficiently ready for transmission, several frames I can be sent in sequence. When the transmission stops, the receiver waits until \( T_{2} \) to make sure there is no frame I, the receiver is activated, waits until \( T_{103} \) and sends the RR frame (acknowledge). The transmission process for window size \( (k) = 1 \) and \( k = 5 \) is shown in figure 4 and figure 5 respectively.

![Figure 4. Exchange of frames at k = 1](image1)

![Figure 5. Exchange of frames at k = 5](image2)

For analytical purposes, it can be assumed that the communication process between RTU and Master Station is in perfect condition which aims to get the best results. In the half-duplex connection system, the transmission process consists of several cycles. Each cycle contains up to \( k \) of the information frame and the acknowledgment (RR) frame, as shown in figure 4 and figure 5. The amount depends on the actual transmission parameters, such as \( k \), \( N_1 \) and \( L \).

3.2.1 Frame transmission time. Bit stuffing additions can increase the transmission time, on average with the addition of \( 1/62 \) and the time parameter of the AX.25 protocol, it can be said that the transmission time of an information frame (I) is equivalent to:

\[
T_1 = T_{103} + \frac{63}{62} + \frac{160 + 8N_1}{R_{wl}} \tag{2}
\]

With
\( T_1 \) = the transmission time of a frame I
\( T_{103} \) = time for stabilizing transmitter parameters after starting transmission
\( R_{wl} \) = baudrate transmission

Meanwhile, transmission of RR frame (acknowledgment) lasts for:

\[
T_{RR} = T_2 + T_{103} + \frac{63}{62} + \frac{160}{R_{wl}} \tag{3}
\]

With
\( T_{RR} \) = RR frame transmission time
\( T_2 \) = Response delay time
\( T_{103} \) = time for stabilizing transmitter parameters after starting transmission
\( R_{wl} \) = baudrate transmission

The two equations (2) and (3) express the busy period of the channel during the appropriate frame type transmission process, including the transmitter startup time.
3.2.2. Total transmission time. When the entire data size is the same as N1xk, the transmission process consists of a number of transmission cycles, as shown in Figure 4 and Figure 5. In each cycle, there are up to k frames of information and one RR frame acknowledgment. In accordance with the protocol operating rules, the total transmission time can be expressed:

\[ T_p = T_{103} + k \cdot \left( \frac{63}{62} \cdot \frac{160 + 8N_1}{R_{wl}} \right) + T_2 + T_{103} + \frac{63}{62} \cdot \frac{160}{R_{wl}} \]  

(4)

Or in a simplified form

\[ T_p = T_2 + 2.T_{103} + (1 + k) \cdot \left( \frac{63}{62} \cdot \frac{160}{R_{wl}} \right) + k \cdot \left( \frac{63}{62} \cdot \frac{8N_1}{R_{wl}} \right) \]  

(5)

with

- \( T_p \) = total transmission time
- \( T_2 \) = Response delay time
- \( T_{103} \) = time for stabilizing transmitter parameters after starting transmission
- \( k \) = window size
- \( N_1 \) = maximum data field capacity
- \( R_{wl} \) = baudrate transmission

When the total data size is not the same as N1xk, the latest transmission cycle must be shorter than that allowed by the parameter value. A small decrease in efficiency can be observed in this case, because the last data fragment must be transmitted with a larger protocol overhead (fewer data bits for the same number of control bits). For all data consisting of LD bytes, the number of transmission cycles can be expressed as:

\[ n = \left\lceil \frac{L_D}{N_1 \cdot k} \right\rceil \]  

(6)

With

- \( n \) = number of transmission cycles
- \( L_D \) = length of data sent
- \( k \) = window size
- \( N_1 \) = maximum data field capacity

The transmission time of all data will take place during:

\[ T_p = \left\lceil \frac{L_D}{N_1 \cdot k} \right\rceil \left( \frac{256T_{102}}{2(p+1)} \right) + T_2 + 2.T_{103} + \frac{63}{62} \cdot \frac{160}{R_{wl}} + \left\lceil \frac{L_D}{N_1 \cdot k} \right\rceil \cdot \left( \frac{63}{62} \cdot \frac{8N_1}{R_{wl}} \right) \]  

(7)

With

- \( T_p \) = total transmission time
- \( L_D \) = length of data sent
- \( T_2 \) = response delay time
- \( T_{102} \) = duration of collision avoidance slots (collision avoidance)
- \( T_{103} \) = time for stabilizing transmitter parameters after starting transmission
- \( P \) = persistent parameter, usually equal to 63 which means the probability of transmission is 25%.
- \( k \) = window size
- \( N_1 \) = maximum data field capacity
- \( R_{wl} \) = baudrate transmission

The number 160 in equation (7) is the number of bits consisting of preamble AX.25, header, check sequence, and end markers of the frame [1].

3. Effective throughput
Throughput is a measure of the transfer of bits in a media for a certain period of time. Due to a number of factors, throughput usually does not correspond to the bandwidth specified in the implementation of
physical layers such as Ethernet. Many factors affect throughput. Among these factors is the amount of data, and the transmission time between two stations [9]. The effective throughput of wireless links can be calculated by dividing the size of the data in bits by $T_p$ [11]:

$$V_{wl} = \frac{8L_D}{T_p} \quad (8)$$

4. Efficiency of the protocol
For each set of parameters given, it is possible to estimate the efficiency of the protocol by dividing the time needed for transmitting data bits with the overall transmission time ($T_p$) including the overall protocol overhead [5]. In the case of the AX.25 protocol operation on the half-duplex link, this relationship can be expressed by the following equation:

$$\eta = \frac{kN_18}{R_{wl}(T_2+2T_{103})^{\frac{k}{62}}160+k^{\frac{25}{62}}(160+8N_1)} \quad (9)$$

with:

- $\eta$ = protocol efficiency
- $T_2$ = response delay time
- $T_{103}$ = time for stabilizing transmitter parameters after starting transmission
- $k$ = window size
- $N_1$ = maximum data field capacity
- $R_{wl}$ = baudrate transmission

4. Testing, Result and Analysis

4.1. Effective Throughput of the AX.25 Protocol
The effective throughput calculation of the AX.25 protocol in this study is based on the amount of data transmitted and the determination of the level of radio link transmission on each device. Radio link transmission rates vary at 1.2 kbps, 2.4 kbps, 4.8 kbps and 9.6 kbps. The maximum amount of data set at 256 by considering the size of the data from the MHPP will not exceed the maximum data byte allocation allowed in the AX.25 protocol [5].

This calculation aims to estimate the effective throughput of the AX.25 protocol on the system that has been created. For analysis purposes, it is assumed that the communication process between RTU and MS is in perfect condition with a transmission distance of 100 meters which aims to get the best results. Therefore, it is assumed that the transmission process is only between two stations, namely RTU-001 with MS and RTU-002 with MS and no collusion or error in transmission [3].

Using equation (8), it can be estimated that the effective throughput of the AX.25 protocol for a variety of $N_1$ values (the capacity of the data field in the information frame). As the parameter values for $T_2$ and $T_{103}$ here use the standard reference value used on a commercially available TNC controller, for example, Symek TNC3 controller [8]. $T_{103}$ value = 25 ms, while $T_2 = 28$ ms. The results of calculations are presented in the pictures directed for each 1.2 kbps radio link transmission, 2.4 kbps, 4.8 kbps and 9.6 kbps.

In the graph presented, it can be seen that increasing the window size and data field capacity will increase effective throughput which does not depend on the transmission rate. For smaller window sizes, not greater than $k = 4$, when the length of the data field is doubled, the throughput will double. For larger window sizes, the biggest increase in throughput is for data fields of 16 bytes and 64 bytes. Further enlargement of the data field still brings advantages, but slower throughput increases. This phenomenon is particularly evident for $k = 7$ at 1.2 kbps and for non-acknowledged transmissions of 1.2 kbps or 9.6 kbps.

The curve representing the dependence between window size and throughput is divided into several segments. The biggest increase in throughput is almost linear between sizes $k = 1$ and $k = 3$. The next segment, between sizes $k = 3$ and $k = 5$, shows a smaller increase in throughput. In the diagram you can
see the big difference between the results achieved for the values of k = 6 and k = 7. This is due to the time T2, which is not used for k by 7, because the AX.25 protocol does not allow larger information frame sizes to be sent sequentially. If for a smaller window (k) size, the sender can mark the latest frame in sequence by setting the Poll / Final bit on the control field frame, the difference will be much smaller, and the protocol efficiency will be higher.

4.2. Efficiency Estimation of the AX.25 Protocol

This estimation aims to see the efficiency of AX.25 protocol performance on the system that has been made. For analysis purposes, it is assumed that the communication process between RTU and MS is in perfect condition which aims to get the best results.

For each given parameter, it is possible to estimate the efficiency of the protocol by dividing the time needed for data transmission with the overall transmission time (TP) including the overall protocol overhead. In the case of the AX.25 protocol operation on the half-duplex link, this relationship can be expressed by equation (2) [8]. This calculation is done by varying the value of the window size starting from k = 1 to k = 7 with the value of N1 = 256.

\[
\eta = \frac{k \cdot N_1 \cdot 8 \cdot R_w(l + 2 \cdot T_{103}) + \frac{63}{62} \cdot 160 + k \cdot \frac{66}{62} \cdot (160 + 8 \cdot N_1)}{R_{w1}(T_2 + 2 \cdot T_{103}) + \frac{63}{62} \cdot 160 + k \cdot \frac{66}{62} \cdot (160 + 8 \cdot N_1)}
\]

With

- \(\eta\) = Efficiency of the protocol
- \(k\) = window size
- \(N_1\) = maximum data field capacity
- \(T_{103}\), transmitter start-up time
- \(T_2\), response delay time

Figure 6. The efficiency of the AX.25 protocol for \(k = 1\) and \(N_1 = 256\)
Figure 7. Efficiency of the AX.25 protocol for \( k = 3 \) and \( N_1 = 256 \)

Figure 8. Efficiency of the AX.25 protocol for \( k = 4 \) and \( N_1 = 256 \)

Figure 9. Efficiency of the AX.25 protocol for \( k = 5 \) and \( N_1 = 256 \)
In all the graphs presented, the highest efficiency can be achieved for the maximum values of $N_1 = 256$ and $k = 7$. In this calculation of efficiency estimates, only the parameters of the radio link transmission ($R_{WL}$) and transmitter start-up time ($T_{103}$) are varied.

In the diagram presented in Figure 6 it can be seen that with $k = 1$ and $N_1 = 256$ values, the efficiency of the protocol ranges from 40% to below 80%, an increase in $T_{103}$ will reduce the efficiency of the protocol. This relationship is very dependent on the level of radio link transmission. Whereas in Figure 7 with the values of $k = 2$ and $N_1 = 256$, the level of protocol efficiency ranges from 60% to below 90%.

In the graph presented in Figure 7 with a value of $k = 7$ and $N_1 = 256$, the efficiency of the AX.25 protocol can reach 90% for the transmission rate of 1.2 kbps. In all the graphs shown, it can be observed that at transmission rates of 1.2 kbps, 2.4 kbps, 4.8 kbps, and 9.6 kbps the decrease in protocol efficiency tends to be linear with respect to changes in $T_{103}$ and does not have a significant impact on changes in transmitter start-up time. For all given $k$ values, when $T_{103} = 0$, regardless of transmission rate, the protocol can achieve an efficiency of around 90%. In practice, this short transmitter start-up time cannot be used because of the nature of the RF transceiver used.

5. Conclusion

The results presented show that the performance of the AX.25 protocol is very optimal in the process of sending data from the RTU using KYL-1020U radio. TNC hardware that was built using Arduino 328 can control the data exchange between RTU-1 and RTU-2 stations very effectively.

In all test results, data can be seen that the highest efficiency can be achieved for the maximum values $N_1 = 256$ and $k = 7$. In the diagram presented can be seen that with $k = 1$ and $N_1 = 256$, the efficiency of the protocol ranges from 40% to below 80%, an increase in $T_{103}$ will reduce the efficiency of the protocol. This relationship is very dependent on the level of radio link transmission. Whereas with the values of $k = 2$ and $N_1 = 256$, the level of protocol efficiency ranges from 60% to below 90%. In testing with $k = 7$ and $N_1 = 256$ values, AX.25 protocol efficiency can reach 90% for transmission rates of 1.2 kbps.

While at transmission rates of 1.2 kbps, 2.4 kbps, 4.8 kbps, and 9.6 kbps the decrease in protocol efficiency tends to be linear with changes in $T_{103}$ and does not have a significant impact on the change in the start-up time of the transmitter. For all given $k$ values, when $T_{103} = 0$, regardless of transmission rate, the protocol can achieve an efficiency of around 90%. In practice, this short transmitter start-up time cannot be used because of the nature of the RF transceiver used.
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