Incorporation of timing properties into adaptive error control method for timely and reliable communication in industrial automation networks

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ABSTRACT

With the evolution of Industry 4.0, factory automation and manufacturing facilities are integrated and interconnected with each other, resulting in the formation of industrial automation networks. In industrial automation networks, transmission of high priority control packets help in monitoring and controlling the industrial machinery automatically. Proper working of these industrial automation networks require timely and reliable communication of control packets dealing with hard real-time traffic due to the presence of highly error prone wireless channels for communication. This study investigates the application of error control approaches to increase the reliability of control packet delivery within the strict deadline of industrial control applications of automation networks. In particular, Adaptive Sub MAC-Hybrid Automatic Repeat reQuest (ASM-HARQ) error control method is proposed in this paper to improve reliability of control packets delivery using both data redundancy and packet retransmission approaches. In order to ensure timely recoverability of any error packets at the receiver, an end-to-end delay packet retransmission metric, $T_{\text{delay}}$, is developed in this study that helps in calculating the time required for packet retransmissions. The performance of ASM-HARQ method and its timing properties is shown through detailed analytical model and validated through simulated experiments in this study.

1. Introduction

Industrial automation networks are composed of distributed control systems and Programmable Logic Controllers (PLCs) that communicate process related data and control data with the actuators, in order to perform the control actions continuously (Nagarajan & Dhanasekaran, 2013). The information that can be communicated over the industrial automation networks is divided into three types: control information, diagnostic information and safety information. The control applications of industrial automation networks transmit control information in the form of control packets between the controllers and act as either input/output of the controller (Moyne & Tilbury, 2007). As the control packets contain hard real-time traffic; they possess strict deadline and reliability requirements. In a typical industrial automation application, control packets deal with actuator position, working speed of industrial machinery, tank levels and fluid flow in the automated factory machines (Galloway & Hancke, 2013; Nagarajan & Dhanasekaran, 2017). Proper working of these industrial automation networks requires timely delivery of the control packets without any errors (Winiweski, Schumacher, Jasperneite, & Diedrich, 2014). On the other hand, the reduced cabling, easy setup, low installation costs and reduced danger of cable breakage have made industrial automation and the factory systems adopt wireless technologies, thereby resulting in the formation of wireless industrial automation networks (Zhong, Mengjin, Peng, & Hong, 2010). The wireless industrial automation networks make satisfying strict reliability requirements of hard real-time control packets highly challenging, due to the presence of highly error prone wireless channels because of channel interference and channel fading issues (Nagarajan & Dhanasekaran, 2015).

Li et al. (2017) in a study on Industrial Wireless Networks (IWNs) in the context of Industry 4.0 showed that offering timely and reliable communications are the two key challenging issues besides network longevity and network security. Frotscher et al. (2014) also indicated some of the key challenges of automated IWNs along with the need of addressing these challenges such as reliable and timely communication, safety and optimized energy consumption. Despite of being a challenging issue, it is still important to offer reliable and timely delivery of control packets on automated IWNs as loss of these packets could result in huge loss of money, time and also physical damages (Das & Havinga, 2013). Identifying this importance of offering timely and reliable delivery of control
packets on automated IWNs, this paper intends in developing an adaptive error control method called Adaptive Sub MAC-HARQ (ASM-HARQ) and in adding timing properties to this error control mechanism.

The main contributions of this paper include: (i) proposing a novel ASM-HARQ error-control method, which aims to guarantee reliable delivery of hard real-time traffic in industrial automation networks (ii) developing an end-to-end delay packet retransmission metric, \( T_{\text{delay}} \) which aims to guarantee packet retransmissions within the deadline requirements (iii) deriving an analytical model for quantifying packet error recoverability; and (iv) evaluating the ASM-HARQ performance levels against a chosen reference protocol using simulation experiments.

2. Literature review

Wisniewski et al. (2014) indicated that reliability in the automated IWNs can be achieved by two ways, one of which is through hardware redundancy, where redundant network links are used and the other one is through data redundancy, where redundant data is added to the normal data to restore any errors at the receiver. In the case of automated IWNs, using redundant network links is not a suitable approach as assuring high connectivity among the devices is not practically feasible. Hence, in this paper the second approach of using data redundancy is considered to provide reliable communication in automated IWNs.

In the literature, several studies have already used this data redundancy approach to address the reliability issue of wireless networks (Tsai, Chilamkurthi, Shieh, & Vinel, 2011a; Reed & Chen, 2012). A study conducted by Tsai et al. (2011a), demonstrates a possible approach to offer reliable transmission of video files over the wireless networks. The authors proposed an Adaptive MAC Forward Error Correction (AM-FEC) method that uses Forward Error Correction (FEC) to add redundancy bits for error recovery at the receiver. A packet error rate model proposed by the authors intends in encoding each Mac Service Data Unit (MSDU) frame at a time. Reed and Chen (2012) have developed a network coding method called C-ARQ (Automatic Repeat Request) for error-control and thereby reliability assurance on wireless data networks. This C-ARQ uses packet retransmissions for error recovery and processes the data in the form of blocks. A recent study by Gunaseelam, Liu, Chamberland, and Huff (2010) has tackled this reliability problem through Hybrid ARQ model that controls errors occurring on a wireless network through a combination of data redundancy and retransmissions. Other related studies include Forward Looking-FEC (Tsai, Shieh, Huang, & Deng, 2011b), Link Layer HARQ (Hong, ShuYa, Ning, & Liang, 2008) and Packet embedded error control (Soltani, Misra, & Radha, 2009).

Despite the efficiency of these existing solutions, none of them have actually considered the reliability problem when dealing with hard real-time traffic on industrial networks. Taking the strict deadline requirements of the control packets in automated IWNs, guaranteeing reliable transmission of the hard real-time traffic before the deadline is the most crucial requirement of the industrial automated networks. One of the existing studies that actually dealt with this problem is done by Ganjalizadeh, Jonsson, and Kunert (2014). A reliability enhancement framework is proposed for hard real-time traffic on packet-switched networks used for industrial applications. Another related study is a survey carried out by Danielis et al. (2014) on the reliable communication methods for hard real-time traffic on industrial automation environments. Despite critically evaluating the existing methods, they are only applicable for Ethernet based industrial systems, which limits their applicability for the automated IWNs that are considered in this study. Other published studies that focused on the reliability issue of industrial automation and factory automation networks are Frotzsche (2014) and Cena, Scanzio, Seno, Valenzano, and Zunino (2016).

Despite the efficiency of these existing studies in addressing the reliability issue of hard real-time traffic in industry automation networks, none of them have explicitly considered the strict deadline requirements of the control packets transmitted over these networks. Recent studies by Tsang, Gidlund, and Akerberg (2016) and Li et al. (2017) on the current trends of IWNs showed that besides reliable communication, timely communication must be guaranteed for hard real-time traffic in order to ensure the delivery of control packets before the deadline. Several methods are developed in the literature to offer timely delivery of the data like Wireless Token Ring Protocol (WTRP) by Ergen, Lee, Sengupta, and Varaiya (2004), Wireless Dynamic Token ring Protocol (WDTP) by Sun, Zhang, and Li (2007) and Improved Wireless Token Ring Protocol (IWRP) by Cheng and Chang (2007). All the techniques assure timely delivery of data by offering deterministic channel access time to each station. According to a study carried out by Yigitbaşı and Buzluca (2008), the existing token ring protocols such as WTRP, WDTP and IWRP can offer time guaranteed data delivery only for the soft real-time traffic. A control plane method developed by Yigitbaşi and Buzluca (2008) aimed at offering guaranteed timely delivery of the hard real-time traffic through timed token protocol. However, this control plane method is based on unrealistic assumption that the underlying wireless channel is reliable and error-free. Moraes, Vasques, Portugal, and Fonseca (2007)
developed Virtual Token Passing- Carrier Sense Multiple Access (VTP-CSMA), a token passing approach for the next generation based communication environments. This approach is applicable even in open communication and adopts a technique of forcing collision resolution through which the real time traffic can be prioritized over the unconstrained traffic.

Other existing studies include Ni, Romdhani, and Turletti (2004) that have made an attempt to offer deterministic delay guarantees on IEEE 802.11 and IEEE 802.11e networks. Scheible, Dzung, Endresen, and Frey (2007) proposed a Wireless Interface for the Sensors and Actuators (WISA) that used multichannel Time Division Multiple Access (TDMA) for uplink and downlink communications in order to offer support for real time data. Some of previous studies have also proposed different wireless standards for the industrial environments such as International Society of Automation, ISA SP100, Wireless HART and Wireless Networks for Industrial Automation/ Process Automation (WIA-PA). Despite these existing approaches being adopted to assure timely delivery of the packets, they face limitations like considering only soft real-time traffic and/or ignoring the reliability requirements of error-prone wireless channel in automated IWNs. In addition, the proposed ASM-HARQ method intends in addressing both reliability and timely requirements of hard real-time traffic of automated IWNs. This is done by adding timing properties to the adaptive error control approach.

3. Proposed adaptive sub MAC-HARQ (ASM-HARQ)

In this section, we describe the proposed error control method for reliable communication of time-critical control packets on wireless networks. ASM-HARQ is an error-control method that integrates error-correction and error-detection techniques to control the errors occurring in the wireless communication and to guarantee reliable data delivery. The novelty of the proposed ASM-HARQ method lies in combining the adaptive nature, reducing the size of encoding unit and using a combination of FEC and ARQ for error-control. The working of ASM-HARQ at sender and receiver to assure reliable delivery of the control packets is detailed below.

3.1. ASM-HARQ at sender

The ASM-HARQ uses an adaptive technique to select the FEC redundancy information based on the channel conditions. The adaptive technique makes the proposed error control mechanism work at the receiver to calculate the average packet loss rate, Burst Bit Error (BBER) length and Round Trip Time (RTT) of the wireless channel.

This information is sent to the sender as channel feedback and using this information, the sender decides the fragmentation size of MAC Protocol Data Unit (MPDU) to MAC Service Data Units (MSDUs) and the FEC redundancy size of each Reed-Solomon (RS) block. The adaptive nature of the proposed error control method helps in minimizing the congestion levels in automated IWNs as the selection of FEC redundant bits is based on the current channel condition. Based on the selected MPDU fragmentation size, ASM-HARQ fragments each MPDU into MSDUs as given in Figure 1.

On the other hand, the proposed method differs from the existing methods by fragmenting the MSDUs further into two equal halves. The main reason of fragmenting MSDUs further is to change the encoding unit from MSDU in Tsai et al. (2011a) to MSDU/2. By choosing the fragmentation size as sub-MSDU (MSDU/2), the number of FEC redundancy bits that can be accommodated in each encoding unit increases, due to the ability of adding more number of bits to build sub-MSDU into a MAC frame.

With the placement of higher data redundancy bits in sub-MSDU than each MSDU frame, the probability of error recovery for sub-MSDU frame increases. This is based on the fact that RS codes that are used for generating FEC redundancy bits in this proposed approach can recover all the bit errors if the number of bit errors is less than half of the FEC redundancy bits (Kumar & Gupta, 2011; Lacan, Roca, Pellet, & Pellet, 2009). Hence, the idea of considering sub-MSDU as an encoding unit can be justified based on its ability to increase the chance of error recovery through FEC redundancy bits. Another reason that justifies the selection of sub-MSDU is its ability in reducing the packet error, which is defined as the number of received packets with errors divided by the total number of received packets. This reduction in packet error rate due to sub-MSDU encoding unit, the number of retransmissions required for error recovery also reduces.

Even though change in encoding unit to sub-MSDU increases the processing overhead at the sender, reliability assurance of the control packets is given higher priority in this approach and also the current technological advancements have minimized the problem of resource constraints for automated IWNs. Therefore, based on the resource availability at the sender and the receiver, the fragmentation of MSDU can be done further to reduce the packet error rate and the number of re-transmissions. All these steps of ASM-HARQ occurring at the sender are shown in Figure 1.

At the sender, the MAC header is slightly altered to include the Number of FEC redundancy bits (as NFEC) to each sub-MSDU unit (as the same bits of FEC redundancy
is added to all sub-MSDU units) as shown in Figure 2. This value of NFEC is used at the receiver in the decoding process. The other crucial technique used in the proposed error control method is HARQ. This HARQ implies that the proposed method combines the properties of both FEC and ARQ methods. This way of combining both FEC and ARQ mechanisms helps HARQ technique offer good reliability, flexibility and throughput. By implementing ARQ controller at the sender, each MAC frame is copied into it before sending it to the receiver.

3.2. ASM-HARQ at receiver

The working of ASM-HARQ method at the receiver to detect and correct the errors is given in the flowchart in Figure 1. As given in Figure 1, when the packet is received, the receiver initially checks if the calculated and received Cyclic Redundancy Check (CRC) checksum values are equal. If both are equal, it implies errors are not present and thereby packet is sent to next level. When the above condition fails, the byte-level decoder checks the condition if Bit Error Length (BEL) < (NFEC/2). When this condition holds true, the RS byte-level decoder recovers all the error bits in the received packets. However, if this condition is not true, then receiver requests for retransmission and simultaneously the RS decoder starts decoding the error frames. This retransmission request is sent to ARQ controller of the sender, which only sends the packets that are identified to be unrecovered at the receiver using FEC redundancy bits. The Number of Retransmission Requests (NRR or \( R_{\text{max}} \)) that is allowed totally depends on the threshold value (\( T_{\text{ret}} \)) of the industrial control applications. The retransmitted packets and simultaneously decoded frames will be used to construct the original MAC frame. The main reason of performing packet re-transmissions and decoding process simultaneously is to recover the errors quickly within the deadline of automated IWN applications.
4. Analytical model

The communications over wireless networks suffer from common problems like burst bit errors. From the known Bit Error Rate (BER) of the wireless channel, a two-state Markov model is adopted to identify the success probability of a byte as $S_{\text{byte}}$.

$$S_{\text{byte}} = (1 - \text{BER}) \left(1 - \frac{\text{BER}}{(\text{BBEL})(1 - \text{BER})}\right)^7$$

In Equation (1), Burst Bit Error Length (BBEL) specifies the number of successive bits that are error and measured in the unit ‘number of bits’. $S_{\text{byte}}$ is generated in Equation (1) based on the concept that the byte of 8 bits can reach the destination successfully if the first bit is in good state, as there is a great chance for the other 7 bits also to be in the same good state.

For a MAC frame of size $(HD + mN)$ bytes the packet error rate $P_{\text{PER}}$ is calculated as follows,

$$P_{\text{PER}} = 1 - (1 - \text{BER})^{HD+mN}$$

In Equation (2), HD is the length of MAC header and trailer of each frame and mN is the length of the MAC frame with N number of MSDUs and each MSDU having m bits. In the proposed ASM-HARQ method, the encoding unit is sub-MSDU (MSDU/2). Hence the packet error rate for ASM-HARQ is given as $P_{\text{SPER}}$ and is calculated as follows,

$$P_{\text{SPER}} = 1 - (1 - \text{BER})^{HD+(mN/2)}$$

Both $P_{\text{PER}}$ and $P_{\text{SPER}}$ in Equations (2) and (3) respectively represent the packet error rate with only difference in the frame size. In both these Equations, packet error rate is defined as the number of received packets with errors divided by the total number of received packets, thereby can be compared with each other. The packet error rate of ASM-HARQ, $P_{\text{SPER}}$ in Equation (3) is comparatively less than packet error rate of existing approaches in Equation (2). This is due to the reduction in the value of the numerator of $P_{\text{SPER}}$ as the encoding unit of the proposed ASM-HARQ is sub-MSDU.

4.1. Packet error recoverability of ASM-HARQ

Packet error recoverability specifies the probability at which the destination node $i$ is able to recover the errors in the received packets either through FEC redundancy bits or through packet retransmissions. An analytical model is used to identify the packet error recovering probability of ASM-HARQ method at the receiver. The Probability of Error Recovery (PER) is expressed as,

$$\text{PER} = 1 - \text{Probability at which error cannot be recovered at the receiver} (P_{\text{unrecovery}})$$

For the existing protocols used in Wireless HART and C-ARQ (Reed & Chen, 2012), reliability is offered through Simple Re-Transmission (SRT) scheme where the error packets or lost packets are retransmitted ‘$m$’ number of times till the receiver node $i$ receives the packets correctly. In such SRT schemes, probability at which error cannot be recovered at the receiver ($P_{\text{unrecovery}}$) occurs when all ‘$m$’ retransmitted packets and the first transmitted packets all arrive at the destination with errors. Hence,

$$P_{\text{unrecovery}} = \left(\epsilon_i\right)^{m+1}$$

Where, $\epsilon_i$ specifies the probability of packet error which indicates the probability at which an error exists in each packet that is received by node $i$. Hence, PER of existing SRT scheme is given as

$$\text{PER} = 1 - P_{\text{unrecovery}}$$

$$\text{PER} = 1 - \left(\epsilon_i\right)^{m+1}$$

In ASM-HARQ method, a packet cannot be recovered from errors when (1) there is a high error rate in the packet received by node $i$, (2) when the receiver $i$ is unable to recover the errors in the received packet using the provided FEC redundancy bits and (3) when the receiver is unable to successfully decode the original message from the retransmitted packets to node $i$. Therefore, the probability at which an error cannot be recovered at the receiver, $P_{\text{unrecovery}}$ of ASM-HARQ mechanism is given as

$$P_{\text{unrecovery}} = \epsilon_i(1 - \gamma_i)(1 - \delta_i)$$

In Equation (7), $\epsilon_i$ specifies the probability of packet error. The variable, $\gamma_i$ specifies the probability that errors
in the received packets can be recovered using FEC redundancy bits and the variable $\delta_i$ specifies the probability that a block can be received successfully when it is retransmitted (Here, block specifies a unit of data transmission like MAC frame or packet).

The probability of packet error ($\varepsilon_i$), depends on the rate at which error occurs in each packet sent over the chosen wireless channel. In other words, the probability of packet error is approximately equal to the packet error rate, in case of a single packet. If $n$ packets are received by the destination, then the probability of packet error in the channel ($\varepsilon_i$), is given as,

$$\varepsilon_i = P_{\text{SFER}} \times n$$

In Equation (8), $P_{\text{SFER}}$ specifies the packet error rate of ASM-HARQ that projects the ratio of the number of received packets having error to the total number of packets received. Substituting value of $P_{\text{SFER}}$ from Equation (3), we get the probability of packet error as,

$$\varepsilon_i = \prod_{j=1}^{n} \left[ 1 - (1 - \text{BER})^{H_D + (mN/2)} \right]^j$$

From Equation (7), it is evident that the probability of the packet recoverability also depends on $\delta_i$, which is the probability at which node $i$ successfully decodes the retransmitted error messages. If the receiver node $i$ is required to decode the retransmitted packets successfully, then the retransmitted packets should not consist of any errors in it and at the same time, this retransmission of the error free packets must be done before the maximum number of the retransmission attempts that are permitted ($R_{\text{max}}$). Hence, $\delta_i$ is given as

$$\delta_i = \frac{R_{\text{max}}}{n} (1 - \varepsilon_i)^x$$

Substituting the values of $\varepsilon_i$, $\gamma_i$ and $\delta_i$ in Equation (7), the probability of packet un-recovery in ASM-HARQ is calculated from Equation (13),

$$P_{\text{unrecovery}} = \varepsilon_i \left( 1 - \sum_{x=0}^{t/2} \binom{n}{x} (S_{\text{byte}})^x (1 - S_{\text{byte}})^{n-x} \right)$$

$$= \left( 1 - \prod_{x=2}^{R_{\text{max}}} \left( 1 - \left( \prod_{j=1}^{n} [1 - (1 - \text{BER})^{H_D + (mN/2)}]^j \right)^x \right) \right)$$

Hence, the probability of packet error recovery of ASM-HARQ mechanism is calculated as $\text{PER} = 1 - P_{\text{unrecovery}}$ from Equation (14)

$$\text{PER} = 1 - \left( \varepsilon_i \left( 1 - \sum_{x=0}^{t/2} \binom{n}{x} (S_{\text{byte}})^x (1 - S_{\text{byte}})^{n-x} \right) \right)$$

$$\times \left( 1 - \prod_{x=2}^{R_{\text{max}}} (1 - \varepsilon_i)^x \right)$$

This analytical model is used to compare the PER of proposed ASM-HARQ in Equation (14) with $\text{PER}'$ of the existing SRT scheme in Equation (6) that is used for error-control.

### 4.2. Timing analysis of adaptive sub-MAC HARQ

The use of HARQ technique in the proposed ASM-HARQ is a great advantage as it uses both FEC and ARQ techniques for error-control. However, this HARQ mechanism suffers from the issues like poor scalability, error recovery overhead and retransmissions (Lee, Simeone, Kang, Rangan, & Popovski, 2015). The timing analysis of ASM-HARQ mechanism is aimed at minimizing the HARQ issues like error recovery overhead and also in satisfying the deadline requirements of time-critical automated IWNs.
Let, $T_{\text{max}_{\text{delay}}}$ be the threshold delay of the control applications that are supported by these automated IWNs. The proposed ASM-HARQ method can provide time-critical and reliable communications with guaranteed delivery of the control packets of industrial applications within the strict deadlines if the time for re-transmission request and packet re-transmission, is less than $T_{\text{max}_{\text{delay}}}$. That is,

$$T_{\text{delay}} \leq T_{\text{max}_{\text{delay}}} \tag{15}$$

In Equation (15), $T_{\text{delay}}$ is the amount of time from the start of re-transmission request by the receiver until it receives the retransmitted packets.

In ASM-HARQ, the packets that cannot be recovered by the receiver using FEC and packets that are lost are requested for re-transmissions. Due to the strict deadlines of the control applications, this re-transmission of the packets in ASM-HARQ is done based on the timing analysis, so that the re-transmitted packets can reach the destination before the deadline. The total delay of packet re-transmission ($T_{\text{delay}}$) in ASM-HARQ is the sum of the end-to-end delay for retransmission request and end-to-end delay for packet re-transmissions.

$$T_{\text{delay}} = \text{End-to-end delay of retransmission request}$$

$$+ \text{End-to-end delay of packet retransmissions} \tag{16}$$

In Equation (16), the end-to-end delay of retransmission request is the time taken for the re-transmission request to reach the sender from the data receiver. The end-to-end delay for packet retransmission is the time taken for the re-transmitted packets to reach destination from the sender. Each of these end-to-end delays is the sum of transmission delay ($d_{\text{trans}}$), propagation delay ($d_{\text{prop}}$) and processing delay ($d_{\text{procs}}$). Therefore,

End-to-end delay of retransmission request

$$= d_{\text{trans}} + d_{\text{prop}} + d_{\text{procs}} \tag{17}$$

End-to-end delay of retransmitted packets

$$= N_{\text{ret}}(d_{\text{trans}} + d_{\text{prop}} + d_{\text{procs}}) \tag{18}$$

In Equation (18), $N_{\text{ret}}$ represents the number of packets retransmitted from source to the receiver. The transmission delay ($d_{\text{trans}}$) specifies the time from first bit till last bit leaving the sending node. The propagation delay ($d_{\text{prop}}$) specifies the time required for a packet to travel from source to destination over the channel. The processing time ($d_{\text{procs}}$) specifies the amount of time required for processing through the seven OSI layers at sender and the receiver.

However, in calculating the end-to-end delay in Equations (17) and (18), queuing delay is not considered based on the assumption that control packets, which are considered in this study are always given highest priority. In the same way, channel access delay or medium access delay is not explicitly considered in calculating end-to-end delay based on the assumption that timed-token protocol is used with Exhaustive Local Allocation Synchronous Bandwidth Allocation (ELA-SBA) scheme in the network to offer deterministic channel access time to each node in the network. As checking the scheduling ability of this ELA-SBA scheme (Zhang, Burns, & Wellings, 1996) showed consideration of channel access delay, this delay is not considered in Equations (17) and (18). Both these assumptions are highly realistic and feasible for a typical industrial application on automated IWNs requiring deterministic access time to the wireless channel.

Substituting Equations (17) and (18) in Equation (16), the total value of $T_{\text{delay}}$ is obtained as,

$$T_{\text{delay}} = [d_{\text{trans}} + d_{\text{prop}} + d_{\text{procs}}]$$

$$+ N(d_{\text{trans}} + d_{\text{prop}} + d_{\text{procs}}) \tag{19}$$

The timing analysis of ASM-HARQ aims to ensure packet re-transmissions before the control application deadline. This will be done when Equation (20) based on Equation (15) is satisfied.

$$T_{\text{delay}} \leq T_{\text{max}_{\text{delay}}} \tag{20}$$

$$d_{\text{trans}} + d_{\text{prop}} + d_{\text{procs}} + N(d_{\text{trans}} + d_{\text{prop}} + d_{\text{procs}}) \leq T_{\text{max}_{\text{delay}}}$$

The metric $T_{\text{delay}}$, when satisfies Equation (20), the proposed ASM-HARQ provides time-critical and reliable communications with guaranteed delivery of the control packets of industrial automation applications within the strict deadlines.

5. Simulation setup

The proposed ASM-HARQ error control method is simulated using Network-Simulator 2 (NS-2). Considering the properties of the automated IWNs like short range local networks, presence of a small number of nodes, transmission of small sized control packets and transmission delay of 20 msec (Galloway & Hancke, 2013; Li et al., 2017; Tsang et al., 2016), a Wireless Local Area Network (WLAN) with 25 nodes is chosen. The current study assumes the arrangement of the nodes in the form of a ring that adopts a timed token protocol; hence a ring topology network is simulated. Configuration of the physical (PHY) layer parameters and MAC layer parameters are done according to
IEEE 802.11a specifications. The value of other parameters used in the simulation is given in Table 1.

The simulation model with a ring topology WLAN created in this study is simulated for nearly 400 s. The timed token protocol with ELA-SBA scheme (Karimireddy & Zhang, 2017; Zhang et al., 1996) is implemented to offer deterministic channel access time to each station.

6. Results and discussion

We compare ASM-HARQ performance against the existing SRT scheme (Song et al., 2008; Reed & Chen, 2012) and AM-FEC (Tsai et al., 2011a). SRT is a simple retransmission scheme that is used in most of the existing methods like Wireless HART and C-ARQ for error-recovery. AM-FEC is proposed by Tsai et al. (2011a) and uses adaptive FEC for error recovery. Even though ASM-HARQ and existing AM-FEC are MAC layer error control methods; they differ in terms of the encoding unit and the approach to control the errors.

Figure 3(a) and (b) shows the comparative analysis of packet error recovery probability of ASM-HARQ with AM-FEC and SRT methods. In Figure 3(a), there is significant improvement (over 30% in maximum) in packet error recovery probability of ASM-HARQ over AM-FEC and SRT schemes. Here, the probability of Packet Error Recovery, PER for ASM-HARQ in Equation (14) is compared with PER of existing SRT scheme in Equation (6). This improvement can be explained based on the fact that conventional retransmission schemes like SRT rely on retransmitting each packet separately till the errors are recovered. The significant improvement of ASM-HARQ over AM-FEC in Figure 3(a) can be explained by the fact that AM-FEC relies on only the FEC redundancy as opposed to ASM-HARQ that uses both FEC redundancy and retransmission for error recovery. There exists a drastic drop in the probability of packet error recovery when the bit error rate reached $10^{-2}$, $10^{-3}$ and $10^{-5}$. This is because, an increase in the bit error rate above $10^{-2}$ results in the decline of the performance of TCP/UDP agents that reside at the transport layer, which are used for re-transmissions.

All these results in Figure 3(a) are obtained by restricting the number of retransmission to 5. However, further decline in the number of retransmissions from 5 to 2 has widened the probability gap between ASM-HARQ and the existing AM-FEC and SRT schemes as given in Figure 3b. This is expected as every retransmission

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**Table 1.** Value of simulation parameters.

| Simulation parameter       | Value                      |
|----------------------------|----------------------------|
| Number of nodes            | 25                         |
| Type of nodes              | Static                     |
| Type of packets            | Control packets            |
| WLAN standard              | IEEE 802.11a               |
| Type of channel            | Wireless channel           |
| Channel model              | Two Ray Ground             |
| Wireless interface sensitivity | −82 dBm                  |
| Channel bandwidth          | 10 MHz                     |
| Noise floor                | −96 dBm                    |
| Frequency band             | 2.4 GHz                    |
| Header length              | 20 μs                      |
| Slot time                  | 9 μs                       |
| SIFS time                  | 16 μs                      |
| SINR preamble capture      | 4 dB                       |
| SINR data capture          | 10 dB                      |
| CWmin                      | 15                         |
| CWmax                      | 1023                       |
| TTRT (Target Token Rotation Time) | 100 s                    |
| τ (Part of TTRT that cannot be used) | 0 s                  |
| Type of traffic            | CBR traffic                |
| Error model                | Markov Error Model         |
| Packet size                | 512 bytes                  |
| Simulation area            | $100 \times 100$          |
| Simulation time            | 400 s                      |

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Figure 3. (a), (b). ASM-HARQ packet error recoverability when retransmissions are 5 and 2 respectively.
provides higher chance of error recovery in SRT scheme that solely depends on packet retransmissions for error recovery. However, in Figure 3(a) and (b), there exists no difference in the packet error recovery probability of AM-FEC as it does not rely on packet retransmissions for controlling the errors. Figure 3(b) reveals a significant improvement in probability of packet error recovery at the receiver of the proposed scheme over existing AM-FEC and SRT schemes, despite of reducing the number of retransmission. This is because of the fact that an increase in the bit error rate increases the packet error probability (from Equations (2) and (3)), through which the number of retransmissions that are required for SRT scheme for error recovery is more than the proposed scheme which uses the appropriate FEC redundancy bits based on block size to recover the errors first besides requesting for re-transmission using HARQ. In Figure 4(a) and (b), the packet error rate of ASM-HARQ is compared with AM-FEC and SRT schemes. All the three schemes experienced an increase in packet error rate with the increase in bit error rate of the channel. This packet error rate increased drastically when the bit error rate reached $10^{-2}$ and above. This rapid increase in packet error rate can be explained based on the fact that the bit error rate and packet error rate are directly proportional to each other based on the formulae in Equations (2) and (3).

As the rate at which a bit is flipped increases, the rate at which packet consisting of errors in the form of bit flip also increases. However, the critical analysis of the graph reveals a fact that the packet error rate of ASM-HARQ
scheme is less than the existing AM-FEC scheme. This is because, the idea of considering sub-MSDU as encoding unit in the proposed ASM-HARQ decreases the size of encoding unit and thereby the probability of packet error decreases as per the formula in Equation (3). Therefore from Figures 3(a) and 4(a), it is evident that considering sub-MSDU as encoding unit in ASM-HARQ resulted in the decline of packet error rate thereby increasing the probability of error recovery than existing methods. Increase in the number of nodes from 25 to 50 in Figure 4(b), has further widened the gap between ASM-HARQ and existing schemes AM-FEC and SRT in terms of the packet error rate. This is expected as increase in the number of nodes increases the network load and network overhead. However, in both cases of Figure 4(a) and (b), despite of the increase in the number of nodes, the simulation and analytical results of ASM-HARQ packet error rate remained almost similar to each other.

The proposed ASM-HARQ mechanism is compared with AM-FEC and SRT in terms of their packet delivery rates as given in Figure 5(a) and (b). From Figure 5(a) and (b), it is evident that for lower and higher simulation time, the packet delivery rate declined with the increase in the number of nodes in the network. This decline in the packet delivery ratio of all the schemes is due to the fact that increase in the number of nodes increases the network overhead and congestion, thereby declining the chance for packet delivery. However, the proposed ASM-HARQ is found to offer higher levels of packet delivery rate of multiple orders of magnitude over the exiting AM-FEC and SRT schemes. This can be explained based on the fact that encoding unit of sub-MSDU in ASM-HARQ achieved lower packet error rate probability (Figure 4(a) and (b)) than AM-FEC that uses MSDU as is encoding unit. Also ASM-HARQ relying on both FEC data redundancy and packet retransmissions is expected to have higher chances of packet delivery given the increased FEC data redundancy than AM-FEC and SRT schemes that solely relies on data redundancy and packet retransmissions respectively.

7. Conclusions

In this paper, an adaptive error control approach with timing properties is proposed to offer reliable and time guaranteed delivery of control packets in reliable industrial automation networks. An end-to-end delay metric $T_{delay}$ is developed to ensure the packet retransmissions within the deadlines of industrial automation applications. An analytical model is developed in this paper to calculate the packet error recoverability of ASM-HARQ method that ensures to achieve reliable and timely packet delivery in industrial automation networks. Both the theoretical and simulation results revealed the accuracy of the developed analytical model in calculating the packet error recoverability, reducing the packet error rate and improving packet delivery rate. Performance evaluation of ASM-HARQ in Industry 4.0 environments and identification of the optimized number of nodes to improve packet error recovery probability forms an interesting future work.

Disclosure statement

No potential conflict of interest was reported by the authors.

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