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# ON THE SECURITY OF IO-LINK WIRELESS COMMUNICATION IN THE SAFETY DOMAIN

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A PREPRINT

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## ABSTRACT

Security is an essential requirement of Industrial Control System (ICS) environments and its underlying communication infrastructure. Especially the lowest communication level within Supervisory Control and Data Acquisition (SCADA) systems - the field level - commonly lacks security measures. Since emerging wireless technologies within field level expose the lowest communication infrastructure towards potential attackers, additional security measures above the prevalent concept of air-gapped communication must be considered.

Therefore, this work analyzes security aspects for the wireless communication protocol IO-Link Wireless (IOLW), which is commonly used for sensor and actuator field level communication. A possible architecture for an IOLW safety layer has already been presented recently [1].

In this paper, the overall attack surface of IOLW within its typical environment is analyzed and attack preconditions are investigated to assess the effectiveness of different security measures. Additionally, enhanced security measures are evaluated for the communication systems and the results are summarized. Also, interference of security measures and functional safety principles within the communication are investigated, which do not necessarily complement one another but may also have contradictory requirements.

This work is intended to discuss and propose enhancements of the IOLW standard with additional security considerations in future implementations.

**Keywords** IO-Link Wireless · Safety and Security · Industrial Wireless Networks

## 1 Introduction

Due to the steadily growing trend of interconnections within Industrial Control System (ICS) and Cyber-Physical System (CPS) in Industry 4.0, also wireless technologies are increasingly employed across all communication domains.

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This connectivity pervades all communication layers within typical Supervisory Control and Data Acquisition (SCADA) systems from management and planning level to the lower control and field level. Therefore, the attack surface increases not only within Internet Protocol (IP) based networks but also within the lowest field level.

Air-gapping field level systems is considered a sufficient protection measure in combination with physical access control. Especially the wireless technology can enlarge the attack surface drastically within this low level of communication.

But even if field level wireless communication is surely not the most targeted part for attacks on ICS systems, reasonable security measures should be implemented to not become the weakest link within a holistic security concept.

Future areas of applications for field level communication may be found in domains (e.g. mobile roaming device) where physical segregation are unfeasible, therefore security aspects become even more urgent.

IO-Link Wireless (IOLW) is an example for a wireless field level communication protocol, commonly used below the field bus level. As a safety specification already exists for the wired IO-Link standard [2], a safety extension for the wireless equivalent shall be feasible in the future.

In the first phase of the IOLW standardization process, security risks considerations were not the focus of the protocol design and therefore, at the moment, no security measures are part of the protocol specification [3]. To protect the IOLW communication within future use cases, security measures are necessary and must be defined and implemented.

While devices that use IOLW communication protocol are constrained in its resources, common state of the art asymmetric cryptographic methods, e.g. Transport Layer Security (TLS), are not feasible here. Thus, trade offs must be accepted, while increasing the security of IOLW communication by security measures. A recent proposal already outlined practical security measures for IOLW, while orienting on common state of the art wireless protocols and its security measures [1].

The contribution of this work is to determine the overall risk for IOLW communication systems, therefore relevant attack scenarios are depicted and the impact from safety and security perspective is investigated. Moreover, already proposed security measures, which are intended to protect the communication, [1] are analyzed. Further security enhancements are derived and its applicability is investigated.

The paper starts with a brief background of IOLW with its key aspects in Section 2. In Section 3 the methodology of the security analysis is depicted. This analysis is described in Section 4. Furthermore, in Section 5 influences of security measures on safety are outlined. The conclusion in Section 6, findings are summarized and future work is discussed.

## 2 IO-Link Wireless

IOLW was developed as an extension of the proven IO-Link standard [4], which is known as Single-Drop digital communication interface (SDCI) or IEC 61131-9 [5]. Within the factory automation structure, IOLW is mainly intended for sensor/actuator field-bus communication [4, 5, 6].

General surveys of IOLW as an open-vendor communication solution for factory automation on the shop floor are given in [7, 6, 8, 9, 10] with a focus on roaming in [11], antenna planning in [12], coexistence in [13, 14, 15], security enhancement in [16, 17] and functional safety [1], and on IOLW testing in [18, 19, 20, 21, 22]. Nevertheless, a short introduction to IOLW is given here.

In a star-shaped topology, IOLW offers bidirectional wireless communication for (cyclic) process data and (acyclic) on-request data between a wireless master (“W-Master”) and wireless devices (“W-Devices”) [3, 6]. The 2.4 GHz ISM band with gaussian frequency shift keying (GFSK) modulation based on the physical layer (PL) of Bluetooth Low Energy (BLE) 4.2 is utilized in combination with a frequency- and time division multiple access (F/TDMA) scheme and a frequency hopping table. The wireless coexistence behavior can be improved by omitting single frequency channels using blocklisting [6, 15]. Wireless bridges (W-Bridges) are standardized to behave similar to W-Devices while offering a wired IO-Link port in order to retrofit legacy systems.

Up to three W-Masters can operate in the same manufacturing cell with each W-Master providing one to five tracks and each track supporting up to eight slots. Single-slot (SSlot) and double-slot (DSlot) W-Devices are specified. SSlot W-Devices offer two (one) octet(s) for payload and are intended for simple sensors or actuators such as switches. DSlot W-Devices offer 15 (14) octets for payload and are suitable for smart sensor applications (the values in the parenthesis include or exclude the obligatory control octet). Within one track, SSlot and DSlot W-Devices can be combined [3]. Up to 120 (SSlot) W-Devices are supported within e.g. a single manufacturing cell [3, 6]. Furthermore, IOLW includes mechanisms to support energy-self-sufficient W-Devices and roaming of W-Devices or W-Bridges between different cells [11].

Compared to other wireless protocols, IOLW provides deterministic media access. Fig. 1 shows that the communication is divided into cycles and sub-cycles. A cycle lasts 5 ms and contains at least three sub-cycles, each of which lasts 1.664 ms.

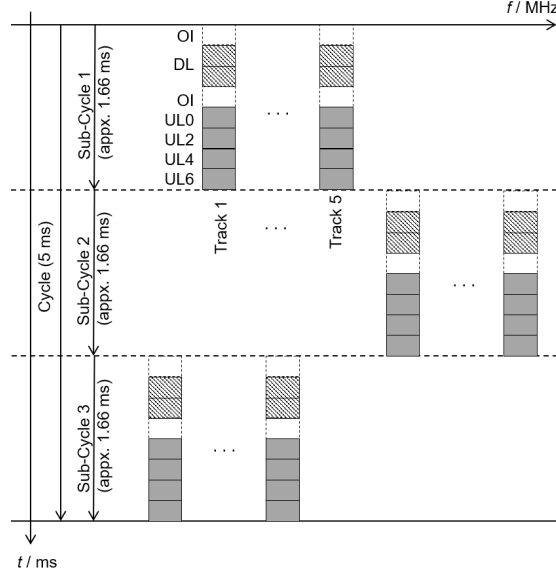


Figure 1: Media access scheme of the IOLW protocol, based on [6].

Between the sub-cycles, frequency hopping takes place with a hopping distance greater than the typical coherence bandwidth of radio channels in industrial environments to increase robustness [13].

In case of a communication error, a repetition is triggered automatically. With one initial transmission trial and up to two repetitions, a cycle time of 5 ms can be achieved. Due to the specific design of the system and a sufficient link budget, this time is ensured with a remaining failure probability that the cycle time is exceeded of  $10^{-9}$  [3, 8]. Therefore, the average receiving power is presumed to be sufficiently high and the system is not interfered. However, IOLW is not suitable for safety and/or security applications, yet. In this paper, the conceptual approach to enhanced IOLW towards a wireless security communication solution for safety critical systems shall be evaluated and relevant security issues should be analyzed.

### 3 Methodology

The used methodology depicted in Fig. 2 starts with identifying potential security issues of IOLW using the IOLW Systems Extensions - Specification [3]. In the next step, security measures proposed in [1] for safety related IOLW applications are identified and in a further step security enhancements are evaluated regarding prerequisites, consequences, safety and security impact and additional mitigation of the specific attack. Finally, security measures affecting functional safety applications are briefly discussed because this impact is critical and shall be kept in mind. This methodology is then utilized in the following Sections 4 and 5.

## 4 Security Analysis

In this section, an analysis of potential attack surfaces of IOLW communication is presented including a threat and risk analysis.

### 4.1 Security Issues of IOLW

Within this section known security issues and weaknesses of IOLW protocol design are outlined. Therefore, the design of the frequency hopping table and the pairing sequence are described. Next, attacks on cryptographic measures are

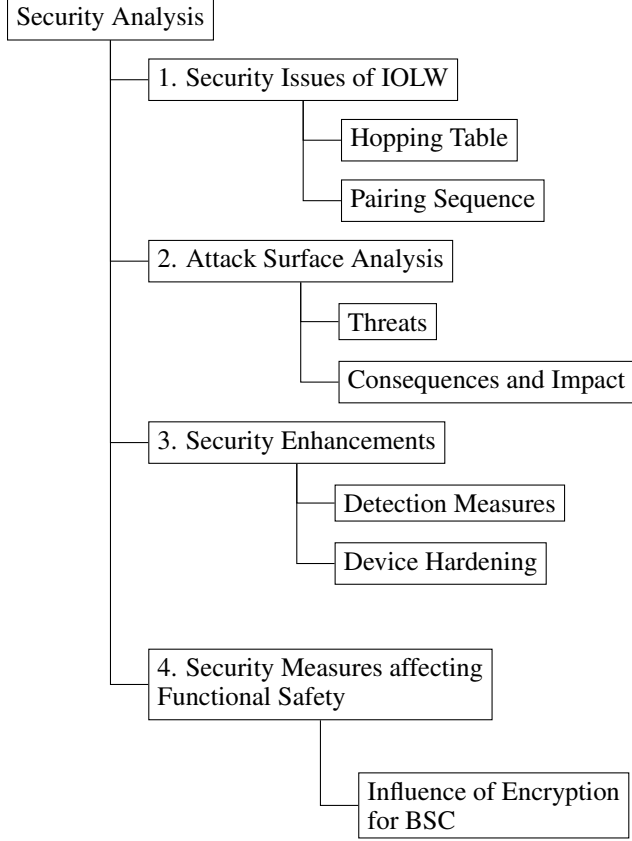


Figure 2: Methodology of Security Analysis

described in detail.

#### 4.1.1 Frequency Hopping Table

IOLW defines dedicated channel hopping sequence algorithms to compute the frequency hopping tables for a W-Master and its W-Devices. These channel hopping sequence algorithms depend on the individual W-Master ID to achieve wireless coexistence within neighboring IOLW systems. Additionally, a blocklisting can be utilized to avoid certain frequency channels in the computed hopping table favoring wireless coexistence with other wireless systems nearby. Blocklisting is a mechanism to avoid on air collision with other wireless systems, such as WLAN. Conventional Bluetooth cannot be blocklisted, since it is an uncoordinated frequency hopper. The blocklist itself uses eighty 1 MHz wide frequency channels and the master configuration setting can be used to suspend frequency ranges [3, p. 35].

The default channel hopping table of IOLW is *HT01* omitting frequencies  $f_{1-2}$  and  $f_{79-80}$ . For configuration, the frequency channels  $f_1$  and  $f_{80}$  are used and  $f_2$  and  $f_{78}$  are Guard-Channels. Blocklisting of each 1 MHz frequency channel is possible. The carrier frequencies  $f_n$  in IOLW are defined according to [3] as  $f_n = f_0 + n \cdot 1 \text{ MHz}$ ; (1) with  $f_0 = 2400 \text{ MHz}$  and  $n = 3$  to 78 (i.e. up to 76 frequency channels) for cyclic data communication. Adaptive Hopping Table - mechanism enables a change of the hopping table of a track while the communication is already running, which may be an improvement of the connection [3, p. 300-302].

#### 4.1.2 Pairing Sequence

IOLW offers different possibilities to pair a W-Device to a W-Master [3]:

- Pairing by UniqueID, which enables the pairing of an unpaired W-Device to a W-Master Port using a pairing request.

- Pairing by Button / Re-Pairing can be used to change a damaged W-Device without using a port and device configuration tool (PDCT) or to pair a W-Device to an unused, pre-configured W-Port during commissioning phase. Therefore, a pairing button or a similar trigger is mandatory for a W-Device.
- Roaming describes a feature to pair a W-Device temporary to a W-Master, which allows predefined W-Devices between multiple W-Masters.

If one W-Master track is in ServiceMode, the configuration channels are available and only in this mode scan, pairing, and roaming activities are possible [3]. But in all cases, messages are sent without encryption and authentication. Also, no shared secret between two devices initially exists or is created, which can be used for initial authentication or as temporary authentication or encryption key. The transfer of a W-Device identification in plaintext is fairly insecure.

For a security-enhanced pairing sequence, a key establishment technique ideally approved by [23] and recommendations for cryptographic key generations [24] are essential. Key exchange possibilities such as Rivest-Shamir-Adleman (RSA), Diffie-Hellman (DH), Elliptic-Curve Diffie-Hellman (ECDH) based key exchange protocol, Elliptic-Curve Menezes-Qu-Vanstone (ECMQV), or Certificate-based pairwise Key Establishment (CPKE) are described and evaluated for security-enhanced IOLW pairing in [1]. Here, an Out-of-band (OOB) commissioning technology using Near-Field Communication (NFC) is suggested to exchange a shared secret. Note that additional hardware is necessary in this case.

#### 4.1.3 Attacks on Cryptographic Measures

In [1], AES-CCM with 32-bit or 64-bit authentication tag is suggested and investigated. Crafting a valid authentication tag would enable an attacker to bypass the cryptographic authentication measure. Therefore, the probability of a birthday attack on the authentication tag shall be evaluated.

$$Adv < \frac{q_{dec}}{2^\tau} + \frac{\sigma^2}{2^n} \quad (1)$$

with

$\tau$ : length of the tag in bits

$\sigma$ : number of encrypted / decrypted blocks

$n$ : block size of the cipher, in bits (128 for AES)

$q_{dec}$ : allowed number of decryption queries

Adv: the probability that an attacker breaks the associated security definition, which shall less than one in 1,000,000 for each random attempt to succeed or a false acceptance to occur [23].

Additionally, in [23] is also stated that “for multiple attempts to use authentication mechanism during a one-minute period, the probability shall be less than one in 100,000 that a random attempt will succeed or a false acceptance will occur”. For each attempt, the value of  $q_{dec}$  shall be ideally 1, respectively as low as possible.

For one IOLW DSlot payload (14 bytes) with a Message Authentication Code (MAC) of  $\tau = 32$  using all three uplink messages (message from a W-Device to a W-Master), the following parameter can be assumed:

$$Adv[\tau = 32] \leq \frac{3}{2^{32}} + \frac{1^2}{2^{128}} \quad (2)$$

$$Adv[\tau = 32] \leq 7 \cdot 10^{-10}$$

For  $\tau = 64$ , the probability of crafting a valid MAC is:

$$Adv[\tau = 64] \leq \frac{3}{2^{64}} + \frac{1^2}{2^{128}} \quad (3)$$

$$Adv[\tau = 64] \leq 1.6 \cdot 10^{-19}$$

The lowest transmission time for one message in IOLW is about 1.664 ms and with two retries about 5 ms. If within two retries no correct message in combination with a valid MAC was sent, the W-Master rejects further messages of this W-Device and W-Port. A reconfiguration is needed, therefore the probability values are already based on 1 min as referred to in [23].

In both cases, the probability is much smaller than one in 1,000,000 that a random attempt will succeed and, hence the attack to craft a valid MAC is very unlikely. Possibly a shorter MAC would also be secure, since a three byte MAC results in a probability of about  $10^{-7}$  (considering that within one minute, the probability shall be less than one in 100,000). With a two byte MAC this consideration of [23] cannot be achieved:

$$Adv[\tau = 16] \leq 4.6 \cdot 10^{-5} \quad (4)$$

If accepting more faulty packets and the allowed number of decryption queries increases by three tries (including each two retries), the availability of the application increases and the probability that an attacker breaks the associated security definition is still low:

$$Adv[\tau = 32, q_{dec} = 10] \leq \frac{10}{2^{32}} + \frac{1^2}{2^{128}} \quad (5)$$

$$Adv[\tau = 32, q_{dec} = 10] \leq 7 \cdot 10^{-9}$$

Increasing the payload (multiple DSLOTS), while only using a four byte MAC for e.g. ten DSLOTS, does not significantly increase the probability that an attacker breaks the associated security definition and is therefore regarded to be sufficient. Here, the approximation that one DSLOT is equal to one encrypted/decrypted block is used.

$$Adv[\tau = 32, \sigma = 10] \leq \frac{3}{2^{32}} + \frac{10^2}{2^{128}} \quad (6)$$

$$Adv[\tau = 32, \sigma = 10] \leq 7 \cdot 10^{-10}$$

This evaluation depicts that the proposed authentication length is sufficient secure for the probability of an attacker breaking the associated security definition [23].

## 4.2 Attack Surface Analysis

This section examines the attack surface for IOLW communication using relevant attack scenarios. Previous mentioned security issues are considered during the creation of attack scenarios.

Protocol specific measures without security background increase the effort for successful attacks drastically. For instance timeliness of communication bursts and knowledge of the frequency hopping table are two additional hurdles to take for executing a successful attack on the wireless communication.

The consequences of different attack scenarios differ and therefore the overall impact must be investigated in detail. Therefore within this analysis section the impact for each attack scenario is rated from a security and a safety perspective. This analysis is used to select and derive suitable protection mechanisms and to rate the effectiveness of already proposed measures.

Security goals within a threat analysis are a common approach to describe the impact of cyber attacks. A very common security goal model is the CIA-triad, which contains the security goals *Confidentiality*, *Integrity* and *Availability*. This concept has its origin in the Information Technology (IT) domain, but is also usable in the Operational Technology (OT) domain. For the use within this analysis, this model is assumed to be sufficient. The most important distinction for the OT environment is the fact, that availability is the most important goal.

While the use of CIA-triad is common practice within security domain, there exist approaches, where this is also mapped onto safety functionality [25].

A safety function relying on IOLW may have two states according to intended disturbance attempts from an attacker - affected or unaffected. No advantage of a finer distinction of impact from this safety perspective is recognized, therefore only a differentiation of impact or no impact is done. The result of this attack surface analysis is depicted in Table 1.

Each attack scenario is described with the prerequisites necessary for successful execution of each threat. Next the consequences of an successful attack are described. These consequences are then rated for its safety and security impact on a generic use case based on IOLW communication. At the end of each attack scenario description additional mitigations are listed, which are intended to protect against the mentioned threat. These mitigations are outlined further within the following section.

Table 1: Possible IOLW attacks influencing the safety and security of its application

Attacks	Prerequisites	Consequences	Safety Impact	Security Impact (CIA-triade)	Additional Mitigation
Denial-of-Service (Flooding)	- Hopping Table, - Knowledge of IOLW config - IOLW W-Master in pairing mode	- W-Master is blocked by processing flooding packets - Valid packets cannot be processed in time - W-Master goes back to initial safe mode	No	Availability	- Early Attack detection using a IOLW Sniffer - Secure transmission of Hopping Table
Jamming	- Jamming W-Device for all frequencies	- W-Master is blocked by processing flooding packets - Valid packets cannot be processed in time - W-Master goes back to initial safe mode	No	Availability	Jammer detection
Replay Attack	- Hopping Table - Sniff valid traffic - Replay sniffed packets	- W-Master is blocked by processing flooding packets - Valid packets cannot be processed in time - W-Master goes back to initial safe mode	No	Availability	Replay attack discovery on IOLW W-Master
Packet Forgery	- Current counter value - Hopping Table	- Rare chances to craft valid MAC and valid payload	Yes	Availability, Integrity	Detection of malicious packets on IOLW W-Master
Packet Forgery (Leaked Key)	- Current counter value - Hopping Table - Leaked key	- Attacker can create valid MAC for any payload.	Yes	Availability, Integrity	IOLW W-Device hardening measures e.g. tamper detection,
Attacker controls IOLW W-Device (backdoor)	- Physical or remote access to IOLW W-Device e.g. via backdoor	Full control to create valid IOLW messages	Yes	Availability, Integrity, Confidentiality	Device hardening, IDS Systems, Anomaly detection in IOLW W-Master

The overall outcome of the attack surface analysis, presented in Table 1 is now discussed. A first noteworthy finding is, that attacks, which only disturb the communication or the timely arrival of messages, are considered having no safety impact. This is backed by the fact, that common safety peers enter a safe state in such events, where no harm originates from the system. These events only lead to impacting the availability of the system and are relevant for security observations.

Critical and not considered within safety analysis is the crafting of valid messages and injecting these into the communication system. Therefore safety functions relying on IOLW communication can be manipulated, e.g. safety sensor values become falsified. These attacks are considered having a severe safety impact.

From a security perspective all considered attack scenarios impact the protection goal availability of the communication system, which is assumed the most targeted goal for attackers. Disturbance of availability leads directly to financial consequences for the asset owner. Attacks like flooding, jamming or replay attack are considered easier in its execution, in comparison to the attack scenarios, which also impact the safety. An attacker with the goal to disturb the availability is assumed to use these attacks instead attacks with more pre-work necessary.

When security enhancements are enabled within the protocol, like proposed in [1], all safety impacting attacks require the bypassing of cryptographic measures, e.g. key knowledge or weak cryptographic measures. These measures are considered to address the threat of safety impact by state of the art cryptography.

But further mitigations are necessary to detect and react early on attack attempts. These are presented in the following section.

### 4.3 Further Security Enhancements

All attack scenarios on IOLW communication require physical proximity to the devices. Therefore, the feasibility of such attacks is generally rated potentially low. Nonetheless, further measures beyond physical access restrictions are considered necessary, since wireless networks may not be physical protect-able for all use cases.

The following enhanced security implementations are described in the proposed IOLW Safety architecture of [1]:

1. Assessment of the automation environment
2. Establishing a one-to-one connection
3. Cryptographic algorithms for IOLW message exchange

The assessment of the automation environment includes the handling of pairing and bonding, security parameter negotiation, encryption, key generation and distribution, and e.g. communication to a Hardware Security Module (HSM).

Establishing a one-to-one connection involves security during commissioning of secrets and security after commissioning of the network key.

In the last part, possible cryptographic algorithms for IOLW message exchange, such as AES-CCM and others e.g. in [16], are evaluated.

Next to these measures, we derived further mitigation from the listed attack scenarios. Attacks on IOLW communication itself have multiple preliminaries. Execution of attacks with real impacts to the communication system are considered difficult, especially due to the need of physical proximity, knowledge of cryptographic key, frequency hopping table and correct time of message exchange.

Further mitigations can be categorized in the following two types, which are depicted now.

#### 4.3.1 Detection Measures

A potential security loophole was identified within the beginning of communication via IOLW. As the hopping table is transmitted in clear text without using any cryptographic measures between the W-Master and W-Device, sniffing of this table is a potential threat. Possession of the frequency hopping table enables certain previous presented attack scenarios.

A cryptographic protected transmission of the table is seen as a possible solution to address this threat. If an security-enhanced pairing exchanges a session or link key to encrypt further communication packets, the frequency hopping table could be adjusted post initial pairing. Another possible solution to protect the transmission of the table can be the transferred via OOB e.g. NFC.

The integrity and confidentiality is addressed by the use of MAC, like proposed in [1]. The limited message length conditions the use of only four bytes or even three bytes for the MAC. The use of truncated MAC authenticator length weakens the state of the art cryptography and does not match recommendations for length. To inhibit brute force attacks, the W-Master should react on receiving wrong MAC authenticators with the transition of the communication system towards a fail-state. The receiving of multiple wrong MAC indicates malicious actions ongoing on the involved W-Device. A shut down of the communication path after detection of irregular behavior reduces the probability of a successful guess for a valid MAC. This behavior results in availability impact of the system, but reduces the potential successful guessing and therefore safety impact. To sum up these observations, the truncated MAC is seen as sufficient measure.

To detect and react early on attack attempts further measures should be implemented within the communication environment. For instance an independent sniffer node could be installed, to detect malicious traffic at an early state of attack. Especially flooding and jamming attempts are addressed by this measure. Since no measures within the protocol design can mitigate flooding or jamming attacks, an early detection of such attacks is an essential building block within an overall IOLW security concept.

#### 4.3.2 Device Hardening

Attacks on the IOLW communication are overall rated rather unlikely, since attacks on remotely accessible devices, e.g. the IOLW master are more likely and the impact is assumed higher. Therefore further device hardening measures on the W-Master device should be investigated in future work.

But also IOLW W-Device should be hardened by implementing a defense-in-depth protection strategy. This addresses the attack scenario of fully controlled IOLW W-Device for instance by applying secure boot, tamper detection and cryptographic protection for key information stored on the W-Device.

The development cycle should therefore be aligned to the IEC 62443-4-1 security norm and security measures from IEC 62443-4-2 should be defined as targeted security levels [26].



## 5 Security Measures Affecting Functional Safety

A functional safety protocol is not initially secure and also vice versa a security protocol is not in general safe, because safety mechanisms detect residual errors whereas security mechanisms try to detect errors/manipulations injected purposely or created unintentionally.

The assumption of a certain residual error probability, such as the probability of undetected errors, with a distribution for the black channel principle is typically based on the binary symmetric channel (BSC) model, e.g. in [27]. Several error types might not be described sufficiently using the BSC model, particularly when using security algorithms in the underlying communication layers [28]. Security algorithms being BSC-preservative and even being viewed as part of the black channel are offering greater efficiency and flexibility [29, 30]. Both papers also describe that fail-safe communication mainly focuses on random errors, but lacks cryptographic techniques protecting against attacks.

A particular problem evolves because some well-established assumptions for functional safe mechanisms may become incorrect using cryptographic algorithms. Therefore, an authenticated and encrypted message may become secure, but the necessary risk reduction for a certain Safety Integrity Level (SIL) classification cannot be guaranteed any longer. In this case, functional safety and (cyber-)security are not independently from each other. This case and complexity is described in detail in [31] with a short safety telegram being transferred encrypted and received with a complete different plaintext as initially intended. The logical consequence is that a sustainable safety protocol must meet modern communication requirements including encryption and the worst possible Bit Error Probability (BEP) of 0.5 being stated in EN 50159. Starting in 2019, a IEC working group (project IEC TR 63069 Ed1) created a framework for functional safety and security, which involves guidance on the common application of IEC 61508 [32] and IEC 62443 [26] in the area of industrial-process measurement, control and automation. The aim of the working group and its technical report is to provide guidance that both fields have no negative influence on each other.

## 6 Conclusion

Need for security within IOLW has been outlined within this contribution using a methodology to identify potential security issues of IOLW, evaluating the security measures proposed in a former publication for safety related IOLW applications, and depicting in a further step security enhancements regarding prerequisites, consequences, safety and security impact and additional mitigation of a specific attack.

The probability of a birthday attack on the authentication tag has been evaluated for different tag and message length showing that the proposed tag length is sufficient secure. Also impact on safety and security goals have been rated within this listed evaluation. The derived security enhancements for the listed attack scenarios have been outlined and can be used for real world applicability evaluation.

The attack scenarios analyzed have all impact on the availability of the communication system. Safety impact requires bypassing of implemented cryptographic measures. Attackers with the intention to disturb the availability will more likely execute attacks without safety impact, since attacks like flooding are easier to carry out.

Furthermore, security measures affecting functional safety have been discussed with the influence of creating new models for the residual error probability when applying cryptographic algorithms within the black channel principle. To maintain existing and previous model calculations, a separation of functional safety and security is still eligible.

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