Open-Fault Resilient Multiple-Valued Codes for Reliable Asynchronous Global Communication Links

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SUMMARY This paper introduces open-wire fault-resilient multiple-valued codes for reliable asynchronous point-to-point global communication links. In the proposed encoding, two communication modules assign complementary codewords that change between two valid states without an open-wire fault. Under an open-wire fault, at each module, the codewords don’t reach to one of the two valid states and remains as “invalid” states. The detection of the invalid states makes it possible to stop sending wrong codewords caused by an open-wire fault. The detectability of the open-wire fault based on the proposed encoding is proven for m-of-n codes. The proposed code used in the multiple-valued asynchronous global communication link is capable of detecting a single open-wire fault with 3.08-times higher coding efficiency compared with a conventional multiple-valued code used in a triple-modular redundancy (TMR) link that detects an open-wire fault under the same dynamic range of logical values.

key words: fault tolerance, m-of-n codes, error detection codes, bidirectional communication

1. Introduction

The performance of digital systems rapidly grows by integrating many processing cores in a single chip thanks to reduction in feature sizes. Transistors and local wires are shrunk as technology node grows, while global wires are not [1] and thus tend to be bottleneck in the complicated systems, such as System-on-Chips (SoC). One of the promising approaches is to use global asynchronous communication based on handshaking among processing cores. The asynchronous communication releases restrictions due to a global clock signal, leading design scalability, flexibility, reliability, and low power dissipation. The systems that utilize global asynchronous communication are realized in fully asynchronous or Global Asynchronous Locally Synchronous (GALS) system [2] that combines local synchronous processing cores and global asynchronous communication.

The global asynchronous communication has been recently used in several applications: Network-on-Chips (NoC)[3], [4], Low-Density Parity-Check (LDPC) decoders [5], [6], commercialized field-programmable gate arrays (FPGA) [7] Ethernet routing chips [8], and digital signal processing (DSP) chips [9]. Some asynchronous communication links have been proposed for high performance systems [10]–[12] as well as reliable systems, where asynchronous communication links are robust against various faults, such as transient and permanent faults [13]–[17].

We have proposed high-throughput wire-efficient asynchronous communication links using multiple-valued codes and current-mode circuits [18]–[21] for high-performance GALS or fully-asynchronous systems. In this paper, open-wire fault resilient multiple-valued encoding is introduced for reliable asynchronous global communication links. An open-wire fault is becoming a critical issue in current and future technology nodes where a total interconnection length in a single chip is in kilometer order and it continues to increase [1]. Even a single open-wire fault in the link by electromigration [22] causes fatal errors in a whole system [23].

To realize open-wire fault resilient asynchronous links using multiple-valued codes, we investigate a behaviour of the multiple-valued asynchronous communication link previously proposed in [20] under an open-wire fault. The multiple-valued asynchronous communication between processing cores (modules) is realized by multiplexing two codewords sent from both modules in order to reduce the number of handshaking steps and wires. In the communication link based on the previous encoding, the multiplexed codeword is wrongly detected as a “valid” state under an open-wire fault, causing wrong data communication. In the proposed encoding, under an open-wire fault, the multiplexed codeword reaches an intermediate state as “invalid” state that properly stops the wrong data communication. In addition, it is mathematically proven that the communication links using the proposed m-of-n codes certainly stop when any single open-wire fault is occurred in the link. The proposed code used in the multiple-valued asynchronous global communication link is capable of detecting a single open-wire fault with 3.08-times higher coding efficiency compared with a conventional multiple-valued code used in a triple-modal redundancy (TMR) link that detects an open-wire fault under the same dynamic range of logical values.

The rest of paper is organized as follows. Section 2 describes a model of an open-wire fault in the multiple-valued asynchronous communication links. Section 3 describes constructions of open-wire fault resilient multiple-valued codes and proves the detectability of the open-wire fault using the codes. Section 4 evaluates coding efficiency.
as a figure-of-merit (FOM) in asynchronous communication links based on the proposed encoding comparing with a duplicated and a triple-modular redundancy (TMR) links based on the conventional encoding. Section 5 concludes the paper.

2. Modeling Open-Wire Faults in Multiple-Valued Asynchronous Communication Links

2.1 Review of Conventional Multiple-Valued Asynchronous Communication Link

Figure 1 shows a block diagram of a conventional multiple-valued asynchronous communication link [20]. In the communication link, input data is encoded as a dual-rail unordered codeword of Data or Spacer at both primary and secondary modules shown in Table 1. Spacer is a separator between two consecutive Data. Both modules send codewords \( A \) and \( B \), simultaneously. The codewords are summed up on the link and then the summed codeword \( C \) is sent back to both modules shown in Table 2.

Figure 2 shows signal states of the codeword \( C(x, x') \), where each axis denotes \( x \) and \( x' \). The four black dots represent the Data states when both modules send ‘Data’, and the white dot represents the Spacer state when both modules send ‘Spacer’. The five states are defined as valid states. The numbers of the states correspond to ones in Table 2. In the multiple-valued asynchronous communication links, the codeword is correctly sent by detecting the valid states. When ‘Data’ is sent, a summed result \( x + x' \) of the codeword \( C(x, x') \) is monotonically increased from logical values ‘0’ to ‘2’. In contrast, when ‘Spacer’ is sent, the summed result \( x + x' \) is monotonically decreased from logical values ‘2’ to ‘0’. Hence, the valid states are detected by using two logical thresholds ‘0.5’ for detecting ‘Spacer’ and ‘1.5’ for detecting ‘Data’, which correspond to the two dashed lines shown in Fig. 2. In the hardware implementation, multi-level current signals are used to represent multiple-valued codewords [18]–[20].

2.2 Fault Model of Open Wires in Multiple-Valued Asynchronous Communication Links

To discuss a reliability of the multiple-valued asynchronous communication link under an open-wire fault, a model of the open-wire fault is described. Figure 3(a) shows a current-flow mechanism in the multiple-valued asynchronous communication links. Under no fault on a wire shown in Fig. 3(b), the current \( I_A \) that corresponds to a logical value in a codeword is generated at the primary module and then mostly divided into two current signals \( I_A/2 \) at the contact.

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**Table 1** Dual-rail encoding of Data and spacer in the conventional multiple-valued asynchronous communication link [20].

| Data | Primary \( A(x, x') \) | Secondary \( B(x, x') \) |
|------|-----------------|-----------------|
| "0"  | (0,1)           | (0,1)           |
| "1"  | (1,0)           | (1,0)           |
| Spacer | (0,0)       | (0,0)           |

**Table 2** Codeword \( C \) in the conventional multiple-valued asynchronous communication link [20].

| State | Primary \( A(x, x') \) | Transmission lines | Secondary \( B(x, x') \) | Data | State |
|-------|-----------------|-----------------|-----------------|------|------|
| "0"   | (0,1)           | (0,2)           | (0,1)           | "0"  | "0"  |
| "0"   | (0,1)           | (1,1)           | (1,0)           | "1"  | "1"  |
| "1"   | (1,0)           | (1,1)           | (0,1)           | "0"  | "0"  |
| Spacer | (0,0)       | (0,0)           | (0,0)           | -     | Spacer |

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**Fig. 2** Signal states of the codeword \( C(x, x') \) in the conventional multiple-valued asynchronous communication link at both modules under no open-wire fault.

**Fig. 3** Current-flow mechanism: (a) link, (b) no fault case, and (c) open-wire fault case.
point [18]. One is sent to the other module and the other one is received at the module itself. Figure 3 (c) shows a current-flow mechanism under an open-wire fault in the link. The current $I_A$ is no longer shunted and hence the whole current is received in the module itself.

Based on the actual hardware behaviours [16], we describe the open-wire fault model in the multiple-valued asynchronous communication link. Figure 4 (a) shows a no-fault model when the link doesn’t have any open-wire faults. In the hardware implementation, as the half of the input current is sent to the other module shown in Fig. 3, the both modules send twice as big as the data that the modules want to send [18]. Hence, the primary module generates “2A” to send “A” to the secondary module that generates “2B” to send “B” to the primary module. These two data are superposed on the wire and the summed data “A+B” is sent back to both modules.

Figure 4 (b) shows the fault model when the link has an open-wire fault. In the primary module, the transmitted data “A” isn’t reach to the secondary module, but is sent to the primary module itself because of the open-wire fault. In addition, the transmitted data “B” from the secondary module isn’t also reach to the primary module. Hence, the summed data in the primary module is “2A”. Similarly, in the secondary module, the summed data is “2B”.

Figure 5 shows signal states of the codeword $C(x, x')$ in the conventional multiple-valued asynchronous communication links at primary module: (a) under an open-wire fault of $x$ and (b) an open-wire fault of $x'$.

2.3 Open-Fault Resilient Asynchronous Communication Link Based on Multiple-Valued Encoding

To prevent the wrong data communication under an open-wire fault, we introduce open-wire fault multiple-valued codes for reliable asynchronous communication links. Figure 6 shows an open-fault resilient asynchronous communication link based on the proposed codes. It can automatically stop sending data when an open-wire fault is occurred. The open-wire fault is detected by timeout of data communication using delay elements at both modules, which then activate “Halt Detection” signals. When both detectors receive the signals, they replace the open-fault wire by spare
ones in order to maintain the functionality of the data communication link. The detailed architecture is described in Sect. 4.3.

In the next section, the proposed multiple-valued codes are described and proven to satisfy the above condition for the open-fault resilient asynchronous links.

3. Open-Fault Resilient Multiple-Valued Codes

The encoding styles of the proposed open-wire fault resilient multiple-valued codes are categorized as one-color and two-color. The one-color encoding uses Data and Spacer as shown in Table 1. As Spacer has to be inserted into two consecutive Data, the number of communication steps is 2 in the multiple-value asynchronous communication links [20]. The two-color encoding uses two different Data: ODD and EVEN [18]. By sending ODD and EVEN alternatively, the two-color encoding eliminates Spacer, which reduces the number of communication steps to 1.

In this section, the proposed open-fault resilient multiple-valued codes are described. Open-fault resilient multiple-valued codes based on one-color or two-color encoding are constructed using m-of-\(n\) codes, which assert \(m\) wires per single data transmission. It is proven that asynchronous data communication using the proposed codes are stopped when any single open-fault is occurred. Assume that the asynchronous communication links using the proposed codes are designed for point-to-point communication shown in Fig. 6.

3.1 One-Color Open-Fault Resilient Codes Based on m-of-n Encoding

3.1.1 Code Construction

A procedure of constructing the proposed open-fault resilient one-color codes based on m-of-n encoding is shown below:

1. Define original codeword sets \(C_p\) and \(C_s\) based on m-of-n encoding for the primary and secondary modules, respectively. Let \(C_p\) be a codeword set \{\(c_{p1}, \ldots, c_{pi}, \ldots, c_{pn}\)\}, where codeword \(c_{pi}\) ∈ \([0,1]^n\). A codeword \(c_{pi}\) is represented as \((c_{pi1}, \ldots, c_{pi,k}, \ldots, c_{pin})\), where \(\sum_{k=1}^{n} c_{pi,k} = m\). \(C_s\) is also represented as well as \(C_p\).

2. Define spacer codewords \(s_p\) for the primary module and \(s_s\) for the secondary module. Let \(s_p\) be \((s_{p1}, \ldots, s_{pk}, \ldots, s_{pm})\), where \(s_{pk} \in [0,1]\). \(s_s\) is also represented as well as \(s_p\). \(s_p\) and \(s_s\) satisfy a condition of \(\sum_{k=1}^{n} (s_{pk} \oplus s_{sk}) = n\).

3. Define data codeword sets \(D_p\) for the primary module and \(D_s\) for the secondary module. Let a data codeword \(d_{pi}\) for the primary module be \((d_{p1}, \ldots, d_{pi}, \ldots, d_{pn})\), where each codeword \(d_{pi}\) is calculated by the formula \(d_{pi} = (c_{pi1} \cdot d_{p1} \cdot \ldots \cdot d_{pin}) = (c_{pi1} + 2 \cdot s_{p1} \cdot c_{pin} + 2 \cdot s_{pn})\). \(D_s\) is also represented as well as \(D_p\).

4. Define codeword sets \(\{D_p, \{s_p\}\}\) for the primary module and \(\{D_s, \{s_s\}\}\) for the secondary module.

In the multiple-valued asynchronous communication, two codewords sent from the primary and the secondary modules are summed up as shown in Fig. 1 and then the summed result is compared with two thresholds to detect Data or Spacer at both modules. When both modules send Data, the summed result becomes the maximum logic value (MAXV). The MAXV is given by

\[
\text{MAXV} = \sum_{k=1}^{n} d_{pi,k} + \sum_{k=1}^{n} d_{sj,k} = \sum_{k=1}^{n} (c_{pi,k} + 2 \cdot s_{pk}) + \sum_{k=1}^{n} (c_{sj,k} + 2 \cdot s_{sk}) = 2m + 2n,
\]

where \(i\) and \(j\) are arbitrary. Note that \(\sum_{k=1}^{n} (2 \cdot s_{pk} + 2 \cdot s_{sk})\) is equal to \(2n\) because \(\forall k, s_{pk} + s_{sk} = 1\) by the definition. When both modules send Spacer, the summer result becomes the minimum logical value (MINV). The MINV is given by

\[
\text{MINV} = \sum_{k=1}^{n} (s_{pk} + s_{sk}) = n
\]

Hence, two threshold values for Data and Spacer are set to \(2m + 2n - 0.5\) and \(n + 0.5\), respectively.

Figure 7 shows an example of the proposed open-wire fault resilient one-color code based on m-of-n encoding, where \(m\) is set to 2 and \(n\) is set to 4. Figure 7(a) shows the original codewords based on 2-of-4 encoding. In the example, both modules use the same assignment of the original codewords to logical values. Note that it is allowed to assign the original codewords to different values at each module. Figure 7(b) shows the spacer codewords at each module. Then, the data codewords are generated using the original and the spacer codewords as shown in Fig. 7(c). In this case, the threshold values for Data and Spacer are set to 11.5 and

| Primary module | Secondary module |
|----------------|------------------|
| Value “0”      | (0 0 1 1)        |
| Value “1”      | (0 1 0 1)        |
| Value “2”      | (0 1 1 0)        |
| Value “3”      | (1 0 1 0)        |
| Value “4”      | (1 0 1 0)        |
| Value “5”      | (1 1 0 0)        |

(a) Original 2-of-4 code

(b) Spacer codeword

(c) Data codeword

Proposed code

Fig. 7 Example of the proposed open-wire fault resilient one-color code based on m-of-n encoding, where \(m\) is set to 2 and \(n\) is set to 4.
3.1.2 Proof of Open-Fault Detectability

**Theorem 1.** Each module designed by using the proposed open-fault resilient one-color code stops data communication when any single open-wire fault is occurred in the communication link.

**Proof.** It is assumed that the i-th wire in the link is in an open-wire fault. Generality of the proof is not lost by the assumption. It is also assumed that module A indicates a module has an i-th element of the spacer codeword that is 1 and module B is the counterpart module of module A. As the spacer codewords at both modules are complementary, module B has an i-th element of the spacer codeword that is 0.

- When both modules send the data codewords, the summation of the codewords becomes $2m + 2n$ under no open-wire fault. When the i-th wire is in an open-wire fault, the summations of the codewords: $\text{MAXV}(\text{module A})$ and $\text{MAXV}(\text{module B})$ monitored by each module are changed as:

  $$\text{MAXV}(\text{module A}) = \text{MAXV} + c_{Aji} - c_{Bki} + 2.$$  \hspace{1cm} (3)

  $$\text{MAXV}(\text{module B}) = \text{MAXV} - c_{Aji} + c_{Bki} - 2.$$  \hspace{1cm} (4)

As the i-th element of the codeword $c_{Aji}$ and $c_{Bki}$ is 0 or 1, $\text{MAXV}(\text{module A})$ becomes $2m + 2n + 1$, $2m + 2n + 2$, or $2m + 2n + 3$, while $\text{MAXV}(\text{module B})$ becomes $2m + 2n - 1$, $2m + 2n - 2$, or $2m + 2n - 3$. It means that the data codeword in the module B CANNOT be detected because $\text{MAXV}(\text{module B})$ never exceeds the threshold value of Data ($2m + 2n - 0.5$). Hence, the module B stops sending new codewords.

- When both modules send the spacer codewords, the summation of the codewords becomes $n$ under no open-wire fault. When the i-th wire is in an open-wire fault, the summations of the codewords: $\text{MINV}(\text{module A})$ and $\text{MINV}(\text{module B})$ monitored by each module are changed as:

  $$\text{MINV}(\text{module A}) = \text{MINV} + 1.$$  \hspace{1cm} (5)

  $$\text{MINV}(\text{module B}) = \text{MINV} - 1.$$  \hspace{1cm} (6)

$\text{MINV}(\text{module A})$ becomes $n + 1$ while $\text{MINV}(\text{module B})$ becomes $n - 1$. It means that the spacer codeword in the module A CANNOT be detected because $\text{MINV}(\text{module A})$ is always larger than the threshold value of Spacer ($n + 0.5$). Hence, the module A stops sending new codewords.

- From the discussion, during single data commutation, both module A and module B stop sending new codewords when any single open-wire fault is occurred.

\[\square\]

3.2 Two-Color Open-Fault Resilient Codes Based on m-of-n Encoding

To realize high-throughput asynchronous data communication links, it is desirable to eliminate the spacer codewords [18], [19]. In this subsection, two-color open-fault resilient codes are defined and its fault detectability is proven.

3.2.1 Code Construction

A procedure of constructing the proposed open-fault resilient two-color codes based on m-of-n encoding is shown below:

1. Define original codeword sets $C_p$ and $C_s$ based on m-of-n encoding for the primary and secondary modules, respectively. Let $C_p$ be a codeword set $\{c_{pi1}, \ldots, c_{pin}, \ldots, c_{pil}\}$, where codeword $c_{pi}$ is represented as $(c_{pi1}, \ldots, c_{pin}, \ldots, c_{pil})$, where $\sum_{i=1}^{n} c_{pi} = m$. $C_s$ is also represented as well as $C_p$.

2. Define intermediate codewords $im_p$ for the primary module and $im_s$ for the secondary module. Let $im_p = (im_{p1}, \ldots, im_{pik}, \ldots, im_{pnl})$, where $im_{pi} \in \{0, 1\}$. $im_p$ is also represented as well as $im_{p1}, im_{p2}$ and $im_{ps}$ satisfy a condition of $\sum_{k=1}^{n} im_{pk} \oplus im_{sk} = n$.

3. Define ODD codeword sets $O_p$ for the primary module and $O_s$ for the secondary module. Let an ODD codeword set $O_p = \{od_{p1}, \ldots, od_{pni}, \ldots, od_{pnl}\}$, where each codeword $od_{pi}$ is calculated by the formula $od_{pi} = (od_{p1i}, \ldots, od_{pin}, \ldots, od_{pni}) = (c_{pi1} + 2 \star im_{p1i} \ldots c_{pin} + 2 \star im_{pin} + 2)$. $O_s$ is also represented as well as $O_p$, where $O_s = \{od_{s1}, \ldots, od_{sij}, \ldots, od_{sid}\}$ and $od_{sij} = (od_{s1}, \ldots, od_{sij}, \ldots, od_{sid})$.

4. Define EVEN codeword sets $E_p$ for the primary module and $E_s$ for the secondary module. Let an EVEN codeword set $E_p = \{ev_{p1}, \ldots, ev_{pni}, \ldots, ev_{pnl}\}$, where each codeword $ev_{pi}$ is calculated by the formula $ev_{pi} = (ev_{p1i}, \ldots, ev_{pin}, \ldots, ev_{pni}) = (c_{pi1} + 4 \star im_{p1i} \ldots c_{pin} + 4 \star im_{pin} + 4 \star im_{pni})$. $E_s$ is also represented as well as $E_p$, where $E_s = \{ev_{s1}, \ldots, ev_{sij}, \ldots, ev_{sid}\}$ and $ev_{sij} = (ev_{s1}, \ldots, ev_{sij}, \ldots, ev_{sid})$.

5. Define codeword sets $\{O_p, E_p\}$ for the primary module and $\{O_s, E_s\}$ for the secondary module.

The multiple-valued asynchronous communication using the two-color codes is also realized by sending codewords from both modules as well as one using the one-color codes. When both modules send EVEN, the summed result becomes the MAXV. The MAXV for the two-color codes is also given by

$$\text{MAXV} = \sum_{k=1}^{n} ev_{pik} + \sum_{k=1}^{n} ev_{sij} + \sum_{k=1}^{n} (c_{pik} + 4 \star im_{pik})$$

$$= \sum_{k=1}^{n} (c_{pik} + 4 \star im_{pik})$$
Theorem 2. Each module designed by using the proposed open-fault resilient two-color code stops data communication when any single open-wire fault is occurred in the link.

Proof. It is assumed that the i-th wire in the link is in an open-wire fault. Generality of the proof is not lost by the assumption. It is also assumed that module A indicates a module has an i-th element of the intermediate codeword that is 1 and module B is the counterpart module of module A.

- When both modules send the ODD codewords, the summation of the codewords becomes 2m + 2n under no open-wire fault. When the i-th wire is in an open-wire fault, the summations of the codewords: MINV(module A) and MINV(module B) monitored by each module are changed as:

\[ \text{MINV(module}_A) = \text{MINV} + c_{Aji} - c_{Bki} + 2. \]  
\[ \text{MINV(module}_B) = \text{MINV} - c_{Aji} + c_{Bki} - 2. \]

As the i-th element of the codeword \( c_{Aji} \) and \( c_{Bki} \) is 0 or 1, MINV(module A) becomes 2m + 2n + 1, 2m + 2n + 2, or 2m + 2n + 3 while MINV(module B) becomes 2m + 2n - 1, 2m + 2n - 2, or 2m + 2n - 3. It means that the ODD codeword in the module A CANNOT be detected because MINV(module A) is always larger than the threshold value of ODD state (2m + 2n + 0.5). Hence, the module A stops sending new codewords.

- When both modules send the EVEN codewords, the summation of the codewords becomes 2m + 4n under no open-wire fault. When the i-th wire is in an open-wire fault, the summations of the codewords: MAXV(module A) and MAXV(module B) monitored by each module are changed as:

\[ \text{MAXV(module}_A) = \text{MAXV} + c_{Aji} - c_{Bki} + 4. \]
\[ \text{MAXV(module}_B) = \text{MAXV} - c_{Aji} + c_{Bki} - 4. \]

As the i-th element of the codeword \( c_{Aji} \) and \( c_{Bki} \) is 0 or 1, MAXV(module A) becomes 2m + 4n + 1, 2m + 4n + 2, or 2m + 4n + 3 while MAXV(module B) becomes 2m + 4n - 1, 2m + 4n - 2, or 2m + 4n - 3. It means that the EVEN codeword in the module B CANNOT be detected because MAXV(module B) never exceeds the threshold value of Even state (2m + 4n - 0.5). Hence, the module B stops sending new codewords.

- From the discussion, during single data commutation, both module A and module B stop sending new codewords when any single open-wire fault is occurred in the link.

\[
\begin{align*}
\text{MINV} & = \sum_{k=1}^{n} od_{pk} + \sum_{k=1}^{n} od_{skj} \\
& = \sum_{k=1}^{n} (c_{pk} + 2 \ast im_{pk}) \\
& + \sum_{k=1}^{n} (c_{skj} + 2 \ast im_{skj}) \\
& = 2m + 2n, \\
\end{align*}
\]

where i and j are arbitrary. Hence, two threshold values for EVEN and ODD are set to 2m + 4n - 0.5 and 2m + 2n + 0.5, respectively.

Figure 8 shows an example of the proposed open-fault resilient two-color codes, where m is set to 1 and n is set to 4. Figure 8 (a) shows the original two-color 1-of-4 codes that are used for both modules. Note that it is allowed to use different original codes at each module. Figure 8 (b) is the intermediate codewords. The ODD and EVEN codewords are calculated using the original 1-of-4 codewords and the intermediate codeword as shown in Fig. 8 (c). In this case, the threshold values of ODD and EVEN are set to 10.5 and 17.5, respectively.

3.2.2 Proof of Open-Fault-Detectability

4. Evaluation

4.1 Average Logical Values

Table 3 shows comparisons of multiple-valued codes for asynchronous communication links. The conventional 1 encoding [20] is shown in Tables 1 and 2. The conventional 1, the previous and proposed 1 codes are constructed based on one-color encoding and take 2 steps for data communication: Data and Spacer. Conventional 2 and proposed 2
codes are constructed based on two-color encoding (ODD and EVEN) and take 1 step for data communication by eliminating Spacer.

These codes use different amount of logical values. Large logical values require large currents in the hardware implementation when a unit current is fixed [18]–[21]. In order to include the hardware overhead for the evaluation of the efficiency of the multiple-valued codes, average logical values per wire (AL) is defined. The AL is given by:

\[
AL = \frac{\text{MINV} + \text{MAXV}}{2n}.
\]

(13)

For example, in the previous encoding, the number of wire \(n \) is 2, the number of asserted wire in single transmission \(m\) is 1, the MAXV is 6, and the MINV is 2 in [16]. Hence, the AL is 2.

The proposed codewords are constructed based on \(m\)-of-\(n\) codes. \(n\) is the number of wires and \(m\) is the number of “1” in the codeword. The ALs in the proposed encoding are described in Table 3. For example, when \(n\) is set to 4 and \(m\) is set to 1, the original codewords are (0,0,0,1), (0,0,1,0), (0,1,0,0), and (1,0,0,0). The AL in the proposed 1 encoding is 1.75 and that in the proposed 2 encoding is 3.5.

### 4.2 Coding Efficiency

Table 4 shows comparisons of Coding_efficiency of the

| # of wires | Method      | Data_value | Wire_efficiency | AL   | Coding_efficiency | Improvement |
|------------|-------------|------------|----------------|------|-------------------|-------------|
| 2          | Previous    | 2          | 0.5            | 2    | 0.125             | -           |
|            | Proposed 1  | 2          | 0.5            | 2    | 0.125             | 0%          |
|            | Proposed 2  | 2          | 0.5            | 4    | 0.125             | 0%          |
| 4          | Previous    | 4          | 0.5            | 2    | 0.125             | -           |
|            | Proposed 1  | 4          | 0.5            | 1.75 | 0.143             | 14.3%       |
|            | Proposed 2  | 4          | 0.5            | 3.5  | 0.143             | 14.3%       |
|            | Proposed 1  | 6          | 0.646          | 2    | 0.162             | 29.2%       |
|            | Proposed 2  | 6          | 0.646          | 4    | 0.162             | 29.2%       |
| 6          | Previous    | 8          | 0.5            | 2    | 0.125             | -           |
|            | Proposed 1  | 15         | 0.651          | 1.83 | 0.178             | 42.0%       |
|            | Proposed 2  | 15         | 0.651          | 3.67 | 0.178             | 42.0%       |
|            | Proposed 1  | 20         | 0.720          | 2    | 0.180             | 44.0%       |
|            | Proposed 2  | 20         | 0.720          | 4    | 0.180             | 44.0%       |
| 8          | Previous    | 16         | 0.5            | 2    | 0.125             | -           |
|            | Proposed 1  | 28         | 0.601          | 1.75 | 0.172             | 37.3%       |
|            | Proposed 2  | 28         | 0.601          | 3.5  | 0.172             | 37.3%       |
|            | Proposed 1  | 56         | 0.726          | 1.875| 0.194             | 54.9%       |
|            | Proposed 2  | 56         | 0.726          | 3.75 | 0.194             | 54.9%       |
|            | Proposed 1  | 70         | 0.766          | 2    | 0.192             | 53.2%       |
|            | Proposed 2  | 70         | 0.766          | 4    | 0.192             | 53.2%       |
Fig. 9 Example of the proposed open-fault resilient link based on one-color encoding when \( m = 2, n = 4 \): (a) overall, (b) open-wire fault, (c) replacement wires related to one of two groups, and (d) data transmission using spare wires.

open-wire fault resilient multiple-valued codes. The coding efficiency is defined as the figure-of-merit (FOM) of the open-fault resilient multiple-valued codes. It is assumed the number of wires \( n \) is an even number in the current and the subsequent subsections. As the previous code is constructed based on dual-rail encoding, several links designed based on dual-rail coding are used together for parallel data communication \( n \geq 4 \). Data value is defined as the number of logical values that is sent. For example, the previous codewords are \((0, 1)\) and \((1, 0)\) when \( n = 2 \). At that time, the logical values are “0” and “1” and hence the data value is 2.

The data value in the previous encoding is \( 2^{n/2} \) while that in the proposed encoding is \( nC_m \).

As the data value is different at each encoding that uses different number of wires, wire efficiency is defined. The wire efficiency is given by:

\[
\text{Wire\_efficiency} = \frac{\log_2(\text{Data\_value})}{\text{The number of wires}}. \tag{14}\]

The proposed 1 and the proposed 2 codes have the same wire efficiency. The number of codewords in the proposed encoding is larger than that in the previous encoding as \( n \) is increased. The coding efficiency is given by

\[
\text{Coding\_efficiency} = \frac{\text{Wire\_efficiency}}{\text{AL} \times \text{The number of steps}}. \tag{15}\]

The coding efficiency of the proposed 1 code is higher than that of the previous encoding by up to 54.9% when \( m \) is set to 3 and \( n \) is set to 8.

4.3 Open-Wire Fault Resilient Link

Figure 9 (a) shows an example of the open-fault resilient asynchronous communication link based on the proposed one-color 2-of-4 code. The code is described in Fig. 7. Original four wires are grouped as Group 1 and Group 2 based on the spacer codewords. Note that the spacer codewords are complementary. The Group 1 has two wires \( x_3 \) and \( x_1 \) that are “1” in the spacer codeword at the primary module. The Group 2 has two wires \( x_2 \) and \( x_0 \) that are “0” in the spacer codeword at the primary module. The both modules have delay elements to realize a timeout function that detects an open-wire fault.

Figure 9 (b) shows an open-wire fault condition, where \( x_3 \) is open. In this case, the primary module is regarded as module \( A \) and the secondary module is regarded as module \( B \) as described in Sect. 3.1.2. As the \( \text{MAX}(\text{module\_B}) \) is smaller than the threshold value for Data, the secondary module cannot detect Data and hence continues sending Data until the timeout of the secondary module. In contrast, as the \( \text{MIN}(\text{module\_A}) \) is larger than the threshold value for Spacer, the primary module cannot detect Spacer and hence continues sending Spacer until the timeout of the primary module.

Figure 9 (c) shows wire replacements after detecting the open-wire fault. Both modules detect it and then replace the wires of the Group 1 by space wires. They might replace
them at different timing, which would receive a wrong data caused by the replacement. We assume that the wrong data transmission can be recovered at higher layer than the physical one, such as the transport layer. It is because the open-wire fault detection is occurred at just one time and hence it is very rare. Other than the case, the communication links based on the proposed codes send data correctly. After the replacement of the wires at both modules, data transmission restarts using spare wires shown in Fig. 9 (d).

4.4 Performance Comparison

Table 5 shows comparisons of open-wire fault resilient multiple-valued asynchronous communication links (n=8). The maximum current on a wire is calculated using the maximum logic values on a codeword when a unit current is fixed to 100 μA. A duplication method [24] is applied to an asynchronous communication link based on the conventional 2 encoding for detection of an open-wire fault. The duplicated link can detect an open-wire fault, but cannot detect which link has the open-wire fault. Hence, it cannot be recovered from the condition of the open-wire fault. A triple-modular redundancy (TMR) method [25] is also applied to the link based on the conventional 2 encoding for detection of an open-wire fault. The TMR link can mask an open-wire fault without using spacer wires and continues data transmission when an open-wire fault is occurred.

The links based on the proposed 3-of-8 encoding can find one of two groups that has an open-wire fault and hence the number of spare wires is \( \lceil n/2 \rceil \) as described in the previous subsection. The MAXV and the MINV of the proposed encoding are calculated using Eqs. (1) and (2) for the one-color code and Eqs. (7) and (8) for the two-color code. The proposed 1 and the proposed 2 encoding require smaller MAXV and MINV than those of the TMR-based link based on the conventional 2 encoding. The link based on the proposed 1 encoding achieves 3.08× higher coding efficiency compared to those of the TMR-based link, while maintaining the same maximum currents on a wire. The link based on the proposed 2 encoding requires higher currents on a wire than the others, but it operates at one step that is the half of proposed 1.

5. Conclusion

In this paper, we have proposed open-wire fault resilient multiple-valued codes for reliable asynchronous global communication links. Under an open-wire fault, the conventional links might receive data that is not actually sent by detecting indistinguishable states that are the same as the valid states caused by an open-wire fault. The proposed encoding eliminates the indistinguishable states and the proposed codewords reach to invalid states that is distinguishable to valid states under an open-wire fault. By detecting the invalid states, the link based on the proposed encoding makes it possible to stop the wrong data communication. A detectability of an open-wire fault based on the proposed encoding is proven for one-color and two-color m-of-n codes. Compared with a triple-module redundancy (TMR) link based on the conventional encoding, the proposed link achieves 3.08× higher coding efficiency. In addition, the proposed codes achieve up to 54.9% higher coding efficiency than the previously reported open-wire fault codes.

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