Ultrareliable Wireless Communication with Message Splitting

(Invited Paper)

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***Abstract*—Deep fading and multicell interference are the two main limiting factors for the practical realization of ultrareliable wireless transmissions. A recently proposed solution for achieving ultrareliability builds upon the idea of combining the user messages as a single packet, then transmitting the packet using a two-phase relaying strategy in order to harvest diversity. A potential problem with such a strategy is that it may be overly optimistic about the ability of the device to decode the entire message in the first phase. This work devises an alternative approach that splits the per-cell message into the broadcast part and the relay part, thereby enabling layered data transmissions to the receivers of various channel conditions. We first analyze the information theoretic achievable rate of a channel with one sender and two receivers, and show that rate-splitting attains the optimal generalized degree-of-freedom (GDoF) whereas the existing method is suboptimal. Furthermore, we combine rate splitting with successive cancellation to handle the case with multiple cells interfering with each other. Numerical examples show a significant advantage of the proposed rate-splitting method over the existing approaches.**

I. Introduction

Ultrareliable wireless transmission with a target packet error probability of lower than 10^{-5} or even 10^{-9} (as compared to the current 4G system with typical error rate of 10^{-2}) is one of the key requirements for future wireless systems [1]. Ultrareliability for mission critical operations, coupled with the low-latency requirement, is envisioned for a broad range of application use cases, including industrial automation, intelligent transportation, power distribution and healthcare [1]–[3]. This paper focuses on the design of an ultrareliable low-latency wireless network in the context of factory automation. We improve upon a previously proposed two-hop diversity transmission protocol [3], [4] by incorporating a message splitting strategy, and provide both theoretical analysis and numerical results to show that the new approach significantly outperforms the previous method in terms of achieving ultrareliability.

Consider the application scenario in which the controller of an automated production line, after receiving the closed-loop feedback from the sensors, sends control messages wirelessly to the remote actuators in order to stabilize the control processes. However, because of fading, not every actuator has a reliable direct wireless link from the controller. To address this issue, the earlier work [3] advocates a scheme named "Occupy CoW" that enhances network coverage via two-hop transmission[1]. The idea is to combine all the downlink messages as a single packet and to enable the actuators to relay this packet for each other in a two-hop transmission strategy. Briefly, this scheme lets all the actuators try to detect the packet from the controller directly in Phase I, then lets those actuators who have successfully decoded the packet act as relay to assist the controller in re-transmitting the same packet in Phase II, as illustrated in Fig. 1.

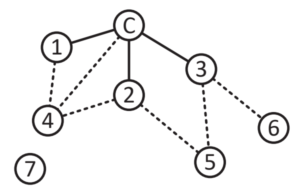

Fig. 1: Two-phase transmission for an isolated production line. Node C is the controller and nodes 1 to 7 are the actuators. The solid lines are the successful transmissions in Phase I, and the dashed lines Phase II. Only node 7 fails to decode the message from the controller.

The strategy of [3] assumes that the encoded aggregate packet either is fully decoded by an actuator, or would be discarded if the actuator fails to decode. This assumption, however, can be limiting, because if an actuator fails to decode the packet in Phase I, then it gains no information. In contrast, this paper proposes a different strategy. We split the packet using layered transmission, so that the relatively weak receivers still have the potential to receive partial information in Phase I. Importantly, this paper shows that the gain of rate splitting is not negligible. For a one-controller-and-two-actuator model, the proposed message-splitting method attains the optimal generalized degree-of-freedom (GDoF) of the network, whereas the Occupy CoW strategy of [3] does not.

Combating interference is yet another challenge for achieving ultrareliability, especially when multiple production lines in a factory setting operate close to each other. The prior work [3] suggests an orthogonal frequency-division multiplexing approach, but the required spectrum bandwidth would then need to scale linearly with the number of controllers. To resolve this issue, the recent work [4] advocates reusing the entire bandwidth in Phase I, while suppressing the interference

[1]More than two hops would incur too much latency.

by successive cancellation. This paper further discusses how the proposed rate-splitting approach can be adapted to the framework of [4].

This work is most closely related to the Occupy CoW method in [3] and a further development in [4] as already mentioned. Other related works in the literature include [5] that lets a subset of successful actuators help with relaying in Phase II in order to enhance energy efficiency and reduce interference, [6] that proposes deploying some stationary relay nodes, and [7] that studies the multi-antenna case.

Notation: $\mathsf{C}(x)$ is used to denote the function $\log_2(1+x)$ for $x \geq 0$, $\mathbb{C}$ the set of complex numbers, and $\mathcal{CN}(0,\sigma^2)$ the zero-mean complex Gaussian distribution with variance σ^2.

II. Occupy CoW Protocol

Consider an industrial factory hall that has L automated production lines, each consisting of one controller and a separate set of remote actuators $\mathcal{K}_i$, $i=1,2,\ldots,L$. We refer to the area occupied by each production line as *cell*. The role of the ith controller is to wireless stream control messages to each of the associated actuators in its cell. Independent control messages of size b bits need to be received at each of the actuators within period T, using a total of W wide spectrum band available for the entire system. Due to fading and interference, not every actuator has a sufficiently strong wireless link from the controller. The recent work of [3] proposes a two-hop transmission framework to enhance the reliability as described below.

The period $[0,T)$ is partitioned into two phases: $[0,0.5T)$ and $[0.5T,T)$. In Phase I, all the controllers transmit signals simultaneously, so each actuator $k \in \mathcal{K}_i$ receives

$$Y_{k,\mathrm{I}}(t) = g_{ki}X_{i,\mathrm{I}}(t) + \sum_{j\neq i} g_{kj}X_{j,\mathrm{I}}(t) + Z_k(t) \tag{1}$$

for $t\in[0,0.5T)$, where $g_{kj}\in\mathbb{C}$ is a realization of the channel from controller j to actuator k, $X_{j,\mathrm{I}}(t)\sim\mathcal{CN}(0,p)$ is the i.i.d. signal transmitted by controller j with a fixed transmit power level p, and $Z_k(t)\sim\mathcal{CN}(0,\sigma^2)$ is the background noise. At the end of Phase I, let $\mathcal{A}_i\subseteq\mathcal{K}_i$ be the set of actuators that have successfully decoded the packet, $i=1,2,\ldots,L$. Subsequently, in Phase II, these actuators in $\mathcal{A}_i$ would assist the controller i with sending the control message to the rest of the actuators in the cell, so each of these actuators $k\in\mathcal{K}_i\backslash\mathcal{A}_i$ would receive

$$\begin{aligned} Y_{k,\mathrm{II}}(t) = \Big(g_{ki}X_{i,\mathrm{II}}(t) + \sum_{\ell\in\mathcal{A}_i} g_{k\ell}X_{\ell,\mathrm{II}}(t)\Big) + \sum_{j\neq i} g_{kj}X_{j,\mathrm{II}}(t) \\ + \sum_{j\neq i}\sum_{\ell'\in\mathcal{A}_j} g_{k\ell'}X_{\ell',\mathrm{II}}(t) + Z_k(t). \end{aligned} \tag{2}$$

for $t\in[0.5T,T)$, where $g_{k\ell}\in\mathbb{C}$ is a realization of the channel from actuator ℓ to actuator k, $X_{j,\mathrm{II}}(t)\sim\mathcal{CN}(0,p)$ is the i.i.d. signal transmitted by controller j, $X_{\ell',\mathrm{II}}(t)\sim\mathcal{CN}(0,p)$ is the i.i.d. signal transmitted by actuator ℓ'.

As mentioned earlier, this two-hop strategy makes each controller i to concatenate all its $|\mathcal{K}_i|$ independent messages into a single $|\mathcal{K}_i|b$-bit message m_i, and requires all the actuators in the cell to decode m_i within the two phases. The rationale for such a design is two-fold. First, the intra-cell interference can be eliminated. Second, those actuators which successfully decode m_i in Phase I can fully help relay this single message in Phase II within its cell.

III. Message-Splitting: Single-Cell Case

A. Reliability of Occupy CoW Protocol

We start with the case of a single cell with $L=1$, i.e., only one production line i. In Phase I, the Occupy CoW protocol lets the controller broadcasts the aggregated message m. Thus, the signal-to-interference-plus-noise ratio (SINR) of actuator k in Phase I is

$$\gamma_{k,\mathrm{I}} = \frac{|g_{ki}|^2 p}{\sigma^2}. \tag{3}$$

The decoding of actuator k is successful if $W\cdot\mathsf{C}(\gamma_{k,\mathrm{I}})\geq R$, and fails otherwise. In Phase II, the controller repeats m along with the successful actuators in $\mathcal{A}_i$. The SINR in Phase II due to cooperation is

$$\gamma_{k,\mathrm{II}} = \frac{|g_{ki}|^2 p + \sum_{\ell\in\mathcal{A}_i}|g_{k\ell}|^2 p}{\sigma^2}. \tag{4}$$

Decoding is successful in Phase II iff $W\cdot\mathsf{C}(\gamma_{k,\mathrm{II}})\geq R$. Observe that $\gamma_{k,\mathrm{II}}\geq\gamma_{k,\mathrm{I}}$, so the failure events in Phase I are given a second chance with a higher SINR. The failure probability of actuator k is

$$\mathsf{Pr}\big[W\cdot\mathsf{C}(\gamma_{k,\mathrm{I}})\leq R \;\text{ and }\; W\cdot\mathsf{C}(\gamma_{k,\mathrm{II}})\leq R\big]. \tag{5}$$

We remark that channel state information at transmitter (CSIT) is not assumed by the Occupy CoW, but the receiver still needs to estimate the channel(s) from its transmitter(s), e.g., by using pilots.

Observe that the Occupy CoW protocol can be inefficient because an actuator would have a complete decoding failure even if its $\gamma_{k,\mathrm{I}}$ is only slightly below the threshold. Next, we introduce a message-splitting method that allows the actuator to partially decode the control message in case it is not capable of decoding the entire message.

B. Proposed Message-Splitting Strategy

The goal is to provide a layered data transmission strategy that can accommodate both strong receivers and weak receivers. Toward this end, we partition the original message m of rate R into m' and m'', respectively with the rates

$$R' = \mu R \quad\text{and}\quad R'' = (1-\mu)R \tag{6}$$

for some $0\leq\mu\leq1$. For Phase I, we allocate a portion $0\leq\lambda\leq1$ of the total transmit power to m' and the rest of the power to m''. The idea is that m' is the part of the message that all the actuators can decode without relaying, while m'' is the message that can benefit from relaying. The proposed message splitting protocol thus consists of:

- Controller broadcasting (m',m'') in Phase I;
- Each actuator decoding m' then trying to decode m'';

- Controller broadcasting m'' in Phase II along with all actuators that have already successfully decoded m''.

The SINRs of actuator k for messages m' and m'' in Phase I can be computed respectively as

$$\gamma'_{k,\mathrm{I}} = \frac{\lambda |g_{ki}|^2 p}{\sigma^2 + (1-\lambda)|g_{ki}|^2 p} \tag{7}$$

and

$$\gamma''_{k,\mathrm{I}} = \frac{(1-\lambda)|g_{ki}|^2 p}{\sigma^2}. \tag{8}$$

In Phase II, on m'' is transmitted, so the entire power should be devoted to it. As a result, if actuator k did not decode m'' in Phase I, its SINR for decoding m'' in Phase II would be

$$\gamma''_{k,\mathrm{II}} = \frac{|g_{ki}|^2 p + \sum_{\ell \in \mathcal{A}_i} |g_{k\ell}|^2 p}{\sigma^2}. \tag{9}$$

Thus, the overall failure probability of actuator k is

$$\begin{aligned} &\mathsf{Pr}\big[W \cdot \mathsf{C}(\gamma'_{k,\mathrm{I}}) < R'\big] + \mathsf{Pr}\big[W \cdot \mathsf{C}(\gamma''_{k,\mathrm{I}}) < R'' \\ &\quad \text{and } W \cdot \mathsf{C}(\gamma''_{k,\mathrm{II}}) < R'' \,\big|\, W \cdot \mathsf{C}(\gamma'_{k,\mathrm{I}}) \geq R'\big]. \end{aligned} \tag{10}$$

Note that the above method reduces to the Occupy CoW method of [3] when $\lambda = \mu = 0$. If we fix λ and μ, then like the Occupy CoW method, our rate-splitting method does not require CSIT.

C. Information Theoretic Analysis

To illustrate the advantage of message-splitting, this section provides an information theoretical analysis for the special case of one controller (node 1) with only two actuators (node 2 and node 3), as shown in Fig. 2. Without loss of generality, node 2 is a stronger receiver than node 3 in the sense that $|g_{21}| > |g_{31}|$. Assume a total of $2n$ channel uses, so that Phase I occupies the channel uses 1 to n, while Phase II occupies channel uses $n+1$ to $2n$. As illustrated in Fig. 2, node 1 transmits a sequence $X_1^{2n} = (X_{1,1}, X_{1,2}, \ldots, X_{1,2n})$ throughout the two phases, node 2 recovers $\hat{m}$ from the received Y_2^n in Phase I, then transmits $X_{2,n+1}^{2n} = (X_{2,n+1}, X_{2,n+2}, \ldots, X_{2,2n})$ based on $\hat{m}$ in Phase II, and node 3 recovers $\hat{\hat{m}}$ based on the received Y_3^{2n} at the end of two phases. We remark that the above channel model is a special version of the *relay broadcast channel* in [8] when the common message transmission and the half-duplex relay are assumed.

First, we discuss the achievability. Clearly, the Occupy CoW method can at most achieve

$$R_o = \frac{W}{2} \min\left\{ \mathsf{C}\left(\frac{|g_{21}|^2 p}{\sigma^2}\right), \mathsf{C}\left(\frac{|g_{31}|^2 p + |g_{32}|^2 p}{\sigma^2}\right) \right\}. \tag{11}$$

The achievable rate of the message-splitting strategy is stated below:

Proposition 1 (Achievability): The rate-splitting method can achieve

$$R_s = R'_s + R''_s, \tag{12}$$

where

$$R'_s = \frac{W}{2} \mathsf{C}\left(\frac{\lambda |g_{31}|^2 p}{\sigma^2 + (1-\lambda)|g_{31}|^2 p}\right) \tag{13}$$

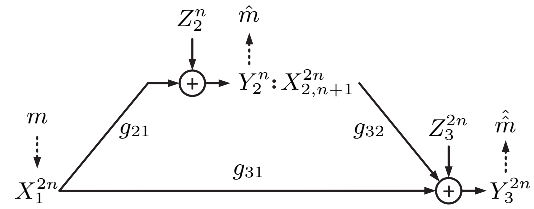

Fig. 2: Node 1 is the controller, node 2 is an actuator, and node 3 is another actuator but with weaker channel, i.e., $|g_{21}| > |g_{31}|$. In the two-hop strategy of [3], node 2 detects $\hat{m}$ in Phase I then forwards it to node 3 in Phase II as a half-duplex relay. In the proposed message-splitting strategy, the message m is split into m' and m''; only m'' is being relayed.

and

$$\begin{aligned} R''_s = \frac{W}{2} \min\Bigg\{ &\mathsf{C}\left(\frac{(1-\lambda)|g_{21}|^2 p}{\sigma^2}\right), \\ &\mathsf{C}\left(\frac{|g_{31}|^2 p + |g_{32}|^2 p}{\sigma^2}\right) \Bigg\}. \end{aligned} \tag{14}$$

Proof: In Phase I, node 2 and node 3 first decode m' by treating m'' as noise, so the maximum R' is $\frac{W}{2} \min_{k \in \{2,3\}} \mathsf{C}\big(\frac{\lambda |g_{k1}|^2 p}{\sigma^2 + (1-\lambda)|g_{k1}|^2 p}\big)$. Note that "min" can be dropped by setting $k = 3$ because $|g_{21}| > |g_{31}|$. After m' is successfully decoded by both node 2 and node 3, only the stronger actuator, node 2, further decodes m''. This decoding would be successful provided that $R''_s \leq \frac{W}{2} \mathsf{C}\big(\frac{(1-\lambda)|g_{21}|^2 p}{\sigma^2}\big)$.

In Phase II, node 1 and node 2 broadcast m'' simultaneously, so node 3 is able to decode m'' if $R''_s \leq \frac{W}{2} \mathsf{C}\big(\frac{|g_{31}|^2 p + |g_{32}|^2 p}{\sigma^2}\big)$. Summarizing the above results yields the achievability. ■

Next, we provide an upper bound on the capacity of this particular relay broadcast channel with common information.

Proposition 2 (Converse): The channel capacity $R^\star$ satisfies

$$R^\star \leq \frac{W}{2} \min\big\{ I(X_1; Y_2), I(X_1; Y_3) + I(X_1, X_2; Y_3) \big\}, \tag{15}$$

which can be further evaluated as

$$\begin{aligned} R^\star \leq \frac{W}{2} \min\Bigg\{ &\mathsf{C}\left(\frac{|g_{21}|^2 p_1}{\sigma^2}\right), \mathsf{C}\left(\frac{|g_{31}|^2 p_1}{\sigma^2}\right) + \\ &\mathsf{C}\left(\frac{|g_{31}|^2 p_1 + |g_{32}|^2 p_2 + 2|g_{31} g_{32}|\sqrt{p_1 p_2}}{\sigma^2}\right) \Bigg\}. \end{aligned} \tag{16}$$

Proof: Let $R_{i,q}$ be the maximum data rate received at node $i \in \{2,3\}$ in phase $q \in \{\mathrm{I}, \mathrm{II}\}$. The Phase I scenario can be recognized as a broadcast channel with common information. Clearly, we have $R_{i,\mathrm{I}} \leq W \cdot I(X_1; Y_i)$. The Phase II scenario can be recognized as a multiple access channel. Since the half-duplex node 2 now works as transmitter, $R_{2,\mathrm{II}} = 0$. In addition, $R_{3,\mathrm{II}} \leq W \cdot I(X_1, X_2; Y_3)$. Combining the above results with $R^\star \leq \min_{k \in \{2,3\}} \{(R_{k,\mathrm{I}} + R_{k,\mathrm{II}})/2\}$ establishes the converse. ■

Comparing the achievable rate and the converse as stated above gives rise to the following main result on the approximate optimality of the proposed message-splitting strategy.

Theorem 1 (Constant Gap Optimality): R_s is always within 1 bit per Hz from the channel capacity $R^\star$ regardless of the values of (g_{21}, g_{32}, g_{31}), whereas $|R^\star - R_o|$ can be arbitrarily large.

Proof: The key step is to set $\lambda = 1 - \min\{1, \sigma^2/(|g_{31}|^2 p)\}$ in Proposition 1. After some algebra, it can be shown that the resulting R_s is within 1 bit per Hz to the upper bound (16), i.e., $\frac{1}{W}|R^\star - R_s| \leq 1$. The gap between $R^\star$ and R_o can be arbitrarily large because the Occupy CoW method is suboptimal in terms of the GDoF, as discussed in the next theorem. ∎

We further examine the asymptotic achievable rate in the high signal-to-noise ratio (SNR) regime. First, the concept of the GDoF is briefly reviewed below.

Definition 1: Fix real numbers $0 \leq \alpha_{ij} \leq 1$. Consider the asymptotic regime in which $|g_{ij}|^2 p/\sigma^2 = P^{\alpha_{ij}}$, $\forall i, j$, while P goes to infinity, the GDoF of the channel as function of α_{ij} is defined as $\lim_{P\to\infty} R/\big(W \cdot \mathsf{C}(P)\big)$.

We now characterize the GDoF of our channel.

Theorem 2 (GDoF Optimality): The message-splitting strategy attains the optimum GDoF of the relay broadcast channel with common information:

$$\begin{aligned}&\mathsf{GDoF}^\star = \\ &\quad \frac{1}{2}\max\Big\{0, \min\big\{\alpha_{21}, \max\{0,\alpha_{31}\} + \max\{\alpha_{31},\alpha_{32}\}\big\}\Big\},\end{aligned} \tag{17}$$

whereas the Occupy CoW method attains a suboptimal GDoF:

$$\mathsf{GDoF}_o = \frac{1}{2}\max\Big\{0, \min\big\{\alpha_{21}, \max\{\alpha_{31},\alpha_{32}\}\big\}\Big\}. \tag{18}$$

Proof: It can be shown that the achievable rate of Proposition 1 with $\lambda = 1 - \min\{1, \sigma^2/(|g_{31}|^2 p)\}$ and the upper bound of Proposition 2 give the same GDoF as in (17). The optimality of $\mathsf{GDoF}^\star$ is then verified. It is easy to see that $\mathsf{GDoF}^\star$ can be strictly higher than GDoF_o. ∎

The above capacity analysis suggests that message-splitting is crucial in guaranteeing the reliability of transmission. Suppose that the target rate is slightly below the capacity $R^\star$ and yet beyond R_o, then the Occupy CoW method would encounter a failure probability arbitrarily close to 100%, whereas rate-splitting with the right splitting ratio can still maintain reliable transmission. Furthermore, we remark that *incremental redundancy* coding [9] can achieve the same rate region as rate splitting, but it requires some extra buffer at the actuator side to store the past signals.

IV. Message-Splitting: Multiple-Cell Case

Inter-cell interference is the main issue when multiple production lines are present close to each other. The earlier work [3] adopts an orthogonalization approach whereby each cell runs the Occupy CoW method individually over a separate sub-band. However, the bandwidth required by this approach need to grow linearly with the number of cells. The more recent work [4] proposes a more aggressive frequency reuse. Assuming that the whole band is fully reused across the cells in Phase I, the approach of [4] lets each actuator try to decode the messages from the nearby cells for interference cancellation prior to the decoding of its desired message. Phase II of [4] remains the same as of [3], i.e., with each cell operates in orthogonal frequency bands. This approach is overall more bandwidth efficient.

The message-splitting approach proposed in this paper can be extended to the multiple-cell case using a similar approach as in [4]. In particular, for each actuator, we order the nearby controllers according to their channel strength, and attempt interference cancellation starting from the strongest controller.

Here, we highlight some of the advantages of using message splitting in conjunction with interference cancellation. First, as compared to the algorithm of [4], the rate-splitting approach proposed in this paper is more likely to be able to cancel inter-cell interference in Phase I, because it allows the actuator to remove m'_j even if it cannot remove the entire m_j. Second, the probability of successful decoding in Phase II is higher in the proposed rate-splitting method because the data rate in Phase II is lowered by the factor $1-\lambda$.

On the other hand, we also remark that since m'_i must be decoded by all the actuators in Phase I in the message-splitting approach, the choice of the rate-splitting ratio is crucial. Indeed, the optimal setting of the rate and power splitting ratios would in general depend on the specific channel realizations. How to best choose these ratios, perhaps in a way that depends only on the statistics of the channels, is an interesting topic for future work.

V. Numerical Examples

We validate the performance of the rate-splitting method by numerically comparing it with the existing algorithms. Given two locations that are d meters apart, we model the pathloss in dB between them as $18.7\lg(d) + 46.8 + 20\lg(0.6)$ if the channel is line-of-sight (LOS), and as $36.8\lg(d) + 46.8 + 20\lg(0.6)$ if the channel is non-line-of-sight (NLOS). Further, we assume that the channel must be LOS when $d \leq 2.5$ m, and would be LOS with a probability of $(1-0.9(1-(1.24-90.61\lg(d))^3)^{1/3}$ otherwise. Thus, deep fading is more likely to happen when the distance increases. We further assume that the standard deviation of the shadowing is 4 dB. Let the total spectrum bandwidth W be 5 MHz, let the transmission period $T = 1$ ms, let the transmit power level $p = 5$ dBm, and let the power spectral density of the background noise be -169 dBm/Hz. Assume that each cell is a 10 m $\times$ 10 m square area in which the controller is at the centre and the actuators are uniformly distributed. For the proposed rate-splitting method, we restrict its parameters to $\lambda \in \{0.1, 0.2, 0.3, 0.4, 0.5\}$ and $\mu \in \{0.5, 0.6, 0.7, 0.8, 0.9\}$, and find the optimal (λ, μ) pair by the exhaustive search.

We first consider a single-cell setup. We set the size of the per-actuator control message $b = 980$ bits. Fig. 3 shows the failure probability versus the number of actuators, averaging over 27000 trials in total. The message-splitting approach outperforms the Occupy CoW protocol significantly, especially in the low failure probability region. For instance, when

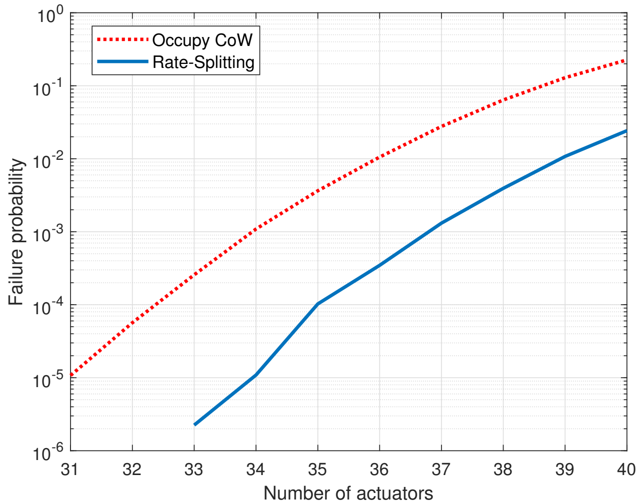

Fig. 3: Single-cell system.

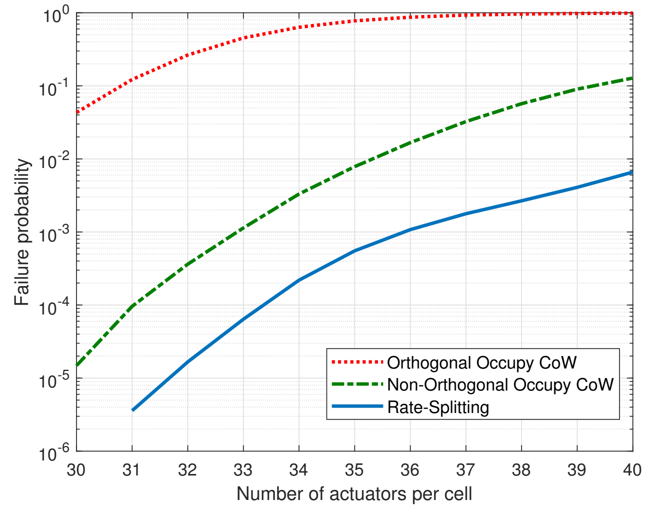

Fig. 4: Multiple-cell system with 9 production lines.

34 actuators are present, the Occupy CoW protocol has a failure probability around 100 times higher than that of the rate-splitting method. Further, the failure probability grows faster with the number of actuators when the Occupy CoW protocol is used. Observe also that no failure occurs under the message-splitting method when there are 32 actuator, so the empirical probability of failure at this point is below $1/(27000 \times 32) \approx 1.2 \times 10^{-6}$.

We further test the multiple-cell case. Assume that 9 cells are deployed as a 3×3 square grid. The cell-centre-to-cell-centre distance between the neighboring cells is 30m. We reduce b to 160 bits because of the interference. The proposed message-splitting approach in conjunction with interference cancellation is compared with two existing methods: the orthogonalization approach of [3] for both Phase I and Phase II, referred to as "orthogonal Occupy CoW", and the method of [4] with reusing the whole bandwidth in Phase I and orthogonalizing Phase II, referred to as "non-orthogonal Occupy CoW". Fig. 4 shows the average result across 5000 trials. It can be seen that the orthogonal Occupy CoW method performs much worse than the other two methods. As compared to the non-orthogonal Occupy CoW method, the message-splitting method proposed in this paper can cut down the failure probability by more than 10 dB. In particular, the message-splitting method does not encounter any failure in this simulation when 30 actuators are deployed in each cell, so the corresponding failure probability is below $1/(5000 \times 9 \times 30) \approx 7.4 \times 10^{-7}$.

VI. Conclusion

This paper proposes a message-splitting approach that facilitates the ultrareliable wireless communication between the controllers and the actuators of an automated industrial factory environment. In order to utilize the spatial diversity while meeting the latency requirement, our approach adopts a two-hopping framework from the existing works [3], [4], but allows message-splitting in order to facilitate partial message decoding. Considering a single-cell case with one controller and two actuators, we show that the Occupy CoW method used in [3], [4] may lead to a GDoF loss so its achievable rate can be arbitrarily lower than the capacity, whereas our proposed rate-splitting method is optimal in terms of the GDoF. The message-splitting method is further extended to the multiple-cell case. It provides layered transmission that can benefit both the decoding of the desired message and the cancellation of the inter-cell interference so as to enhance the reliability of wireless communication. Furthermore, according to numerical simulation, the proposed message-splitting method reduces the failure probability significantly by more than 10 dB as compared to the existing methods.

References

[1] M. Bennis, M. Debbah, and H. V. Poor, "Ultrareliable and low-latency wireless communication: Tail, risk, and scale," *Proc. IEEE*, vol. 106, no. 10, pp. 1834–1853, Sept. 2018.

[2] P. Popovski, "Ultra-reliable communication in 5G wireless systems," in *1st Int. Conf. 5G for Ubiquitous Connectivity*, Nov. 2014, pp. 26–28.

[3] V. N. Swamy, S. Suri, P. Rigge, M. Weiner, G. Ranade, A. Sahai, and B. Nikolić, "Real-time cooperative communication for automation over wireless," *IEEE Trans. Wireless Commun.*, vol. 16, no. 11, pp. 7168–7183, Nov. 2017.

[4] S. A. Ayoughi, W. Yu, S. R. Khosravirad, and H. Viswanathan, "Interference mitigation for ultrareliable low-latency wireless communication," *IEEE J. Sel. Areas Commun.*, to be published.

[5] V. N. Swamy, P. Rigge, G. Ranade, B. Nikolic, and A. Sahai, "Predicting wireless channels for ultra-reliable low-latency communications," in *IEEE Int. Symp. Inf. Theory (ISIT)*, June 2018, pp. 27–30.

[6] N. Brahmi, O. N. Yilmaz, K. W. Helmersson, S. A. Ashraf, and J. Torsner, "Deployment strategies for ultra-reliable and low-latency communication in factory automation," in *IEEE Globecom Workshops (GC Wkshps)*, Dec. 2015, pp. 6–10.

[7] B. Singh, O. Tirkkonen, Z. Li, M. A. Uusitalo, and R. Wichman, "Selective multi-hop relaying for ultra-reliable communication in a factory environment," in *IEEE Int. Symp. Personal Indoor Mobile Radio Commun. (PIMRC)*, Sept. 2016, pp. 4–8.

[8] Y. Liang and V. V. Veeravalli, "Cooperative relay broadcast channels," *IEEE Trans. Inf. Theory*, vol. 53, no. 3, pp. 900–928, Mar. 2007.

[9] G. Caire and D. Tuninetti, "The throughput of hybrid-ARQ protocols for the Gaussian collision channel," *IEEE Trans. Inf. Theory*, vol. 47, no. 5, pp. 1971–1988, July 2001.