Early Detection for Optimal-Latency Communications in Multi-Hop Links

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Abstract—Modern wireless machine-to-machine-type communications aim to provide both ultra reliability and low latency, stringent requirements that appear to be mutually exclusive. From the noisy channel coding theorem, we know that reliable communications mandate transmission rates that are lower than the channel capacity. To guarantee arbitrarily-low error probability, this implies the use of messages whose lengths tend to infinity. However, long messages are not suitable for low-latency communications. In this paper, we propose an early-detection scheme for wireless communications under a finite-blocklength regime that employs a sequential-test technique to reduce latency while maintaining reliability. We prove that our scheme leads to an average detection time smaller than the symbol duration. Furthermore, in multi-hop low-traffic or continuous-transmission links, we show that our scheme can reliably detect symbols before the end of their transmission, significantly reducing the latency, while keeping the error probability below a predefined threshold.

I. INTRODUCTION

Many critical applications require ultra-reliable communication *and* extremely-low latency, e.g., communications between financial trading centers [1], or vehicle-to-vehicle communications for collision warning [2]. As stated by Shannon [3], to achieve ultra-reliable communications (arbitrarily-small error probability), the blocklength must tend to infinity, inducing a high latency. Therefore, critical communication applications use channel codes where short codewords can be transmitted over a noisy channel with an average block-error rate (BLER) smaller than a predetermined target that tends to zero.

Recent results on non-asymptotic fundamental limits of channel coding allow us to approximate the minimum blocklength needed for a targeted BLER given the capacity of a noisy channel [4], [5]. These fundamental results can be applied to one-hop communication systems. On the other hand, research in multi-hop networks has been devoted to constructing transmission schemes with minimal delay [6]–[10]. In these works however, the signaling delay has not been taken into account. Most of these systems need to be synchronized as they are required to wait at the end of a transmitted symbol to make a decision (i.e., *synchronous detection*). Several new waveforms have been proposed to fulfill the low-latency requirements of the next-generation mobile-communication standard (5G) [11]–[13]. Similarly, these waveforms all require synchronization.

An optimal low-latency transmission strategy for schemes employing amplify-and-forward relaying was constructed [14]. It used an early-detection scheme inspired by communications with sequential detection feedback where the transmission ends as soon as the receiver makes the correct decision [15]. However, contrary to [15], that early-detection scheme does not rely on a feedback. In this paper, we investigate the minimal latency in multi-hop systems that employ decode-and-forward (DF) relaying schemes, when either synchronous-detection or early-detection schemes are used. Both work consider an orthogonal frequency-division multiplexing (OFDM)-like signal defined as simultaneous transmission of all symbols in parallel over the channel.

Contributions: The first part of this paper presents a simplification of the early-detection technique from previous work and proves that the resulting scheme has optimal latency in a single-hop system. For simplicity, we assume throughout this paper a power-constrained memoryless additive white Gaussian noise (AWGN) channel. The second part applies this scheme to two common types of multi-hop systems with DF relays, and the latency is proved to be optimal in these systems as well.

II. DEFINITION AND PROBLEM STATEMENT

A. Definition of Channel Coding

Consider a code with blocklength n generating M codewords. We denote the input and output alphabets \mathcal{A} and \mathcal{B} , and a conditional probability measure $P_{\mathbf{Y}|\mathbf{X}}:\mathcal{A}^n\longmapsto\mathcal{B}^n$, in which \mathbf{X} represents an input sequence encoded by an (n,M,ϵ) -code, where $\epsilon>0$ is the block-error probability. \mathbf{Y} , the corresponding output sequence, depends statistically on the input sequence \mathbf{X} through the conditional probability density function $P_{\mathbf{Y}|\mathbf{X}}$. Specifically, in AWGN channels we have:

$$\mathbf{Y} = \mathbf{X} + \mathbf{Z},\tag{1}$$

where $\mathbf{X} \in \mathcal{A}^n$, $\mathbf{Y} \in \mathcal{B}^n$ and \mathbf{Z} is a random vector whose components are independent and identically distributed (i.i.d.) by Gaussian random variables with zero mean and unit variance: $\mathbf{Z} \sim \mathcal{N}(0, \mathbf{I}_n)$ independent of \mathbf{X} , where \mathbf{I}_n denotes the $n \times n$ identity matrix.

Furthermore, we define a list $C = \{1, \dots, M\}$ of M equiprobable messages to be transmitted. Thus, an (n, M, ϵ) -

code has an encoding function $f:\mathcal{C}\longmapsto \mathcal{A}^n$ in which a message $m\in\mathcal{C}$ is chosen and returns a codeword $\mathbf{X}^m=[X_1^m,\cdots,X_n^m]$. All of these input sequences satisfy a maximal-power constraint such that:

$$\|\mathbf{X}^m\|^2 < nPT, \quad m = 1, \dots, M,$$
 (2)

where P is the average received power and T denotes the symbol duration. In addition, consider a decoder $g: \mathcal{B}^n \longmapsto \mathcal{C}$ whose average probability of error does not exceed the BLER ϵ :

$$\frac{1}{M} \sum_{m=1}^{M} P_{\mathbf{Y}|m} \left(g\left(\mathbf{Y} \right) \neq m | M = m \right) \le \epsilon \tag{3}$$

where $P_{\mathbf{Y}|m}$ is the conditional probability that the decoder $g(\mathbf{Y})$ picks up the wrong message when the actual m was transmitted.

The maximum achievable code rate $R^*(\epsilon,n) = \log_2(M)/n$ (bits per channel use) satisfying a required BLER ϵ given a signal-to-noise ratio (SNR) budget $E_s/N_0 = PT$ can be determined for finite-blocklength coding in AWGN channels. It is given by the following theorem [16].

Theorem 1 (Polyanskiy et al. 2010): For a discrete-time AWGN channel with a SNR equal to PT, there exists a (n, M, ϵ) -code such that the maximum achievable code rate $R^*(\epsilon, n)$ for equal-power and maximal-power constraints is given by:

$$R^*(\epsilon, n) \le C - \sqrt{\frac{V}{n}} Q^{-1}(\epsilon) + \frac{1}{2n} \log_2(n) + O(1),$$
 (4)

where $Q^{-1}(\cdot)$ is the inverse complementary Gaussian CDF function and C is Shannon's capacity formula in bits per channel use:

$$C = \frac{1}{2}\log_2(1 + PT) \tag{5}$$

assuming an AWGN channel with zero mean and unit variance. V is the channel dispersion written as:

$$V = \frac{PT}{2} \frac{PT + 2}{(PT + 1)^2} \log_2^2 e.$$
 (6)

The channel dispersion quantifies, under equal capacity, the stochastic variability of the channel relative to a deterministic channel. By assuming that the input sequence is encoded such that $\mathbf{X}^m \in \mathbb{R}^n$ for $m=1,\cdots,M$ and the received signal is $\mathbf{Y} \in \mathbb{R}^n$, we assume that each component of the vector \mathbf{X}^m is transmitted in parallel using an OFDM-like signal.

B. Transmission using OFDM-like Signals

Consider a message m chosen for transmission. Each component of the codeword $\mathbf{X}^m = \{X_1^m,...,X_n^m\}$ is simultaneously transmitted in parallel over the channel via an OFDM-like signal such that:

$$s_m(t) = \sum_{i=1}^n X_i^m \varphi_i(t), \quad 0 \le t \le T,$$
 (7)

where $\varphi_i(t)$ is an orthonormal basis spanning the vector-space of signals. We consider that the decoder receives an output

sequence $\mathbf{Y}_{\tau} = \{Y_{1,\tau}, \cdots, Y_{n,\tau}\}$ for all $\tau \in [0,T]$ such that:

$$Y_{i,\tau} = \int_0^{\tau} (s_m(t) + z(t)) \varphi_i^*(t) dt, \qquad (8)$$

where z(t) is a zero-mean white Gaussian process with power spectral density $N_0/2$. This condition allows the design of an optimal decision rule minimizing the time needed $(\tau \leq T)$ to make a correct decision while maintaining a BLER that does not exceed ϵ .

In AWGN channels, we assume that $\forall \ \delta \tau > 0$ the differential $Y_{i,\tau+\delta\tau} - Y_{i,\tau}$ is i.i.d. $\forall \ i=1,\cdots,n,$ and consider the case of equiprobable signals, i.e., $P_m=1/M$ for all m. It follows that the decoder can do early detection based on a sequential test by considering a threshold $S_m \geq 0$:

$$g(\mathbf{Y}_{\tau}) = \begin{cases} m & \text{if } \exists \ \mathbf{X}^m \text{ s.t. } P(m|\mathbf{Y}_{\tau}) > S_m, \\ \text{wait for } \mathbf{Y}_{\tau+\delta\tau} & \text{otherwise.} \end{cases}$$
(9)

The decoder makes a decision as soon as the posterior probability $P(m|\mathbf{Y}_{\tau})$ reaches a threshold S_m . If the threshold is not reached before the end of the transmitted symbol, the decision is made at t=T.

According to the guidelines set by the binary sequential probability ratio test (SPRT) [14], the threshold S_m can be defined as follows:

$$S_m = \frac{1}{1 + M \sum_{\substack{m'=1\\m' \neq m}}^{M} Q\left(\sqrt{\frac{d_{mm'}^2}{2N_0}}\right)},$$
 (10)

where $Q(\cdot)$ is the complementary CDF of a Gaussian random variable, and $d^2_{mm'}$ is the squared distance between two different codewords.

To reduce the probability of false decision, the cross product between two arbitrary OFDM-like signals $s_m(t)$ and $s_{m'}(t)$ with $m^{'} \in \mathcal{C}$ and $m \neq m^{'}$ is assumed to be approximately equal to zero. In other words $\forall \tau \in [0,T]$, the OFDM-like signals must satisfy:

$$\begin{split} d_{mm'}^{2}(\tau) &= \int_{0}^{\tau} |s_{m}(t) - s_{m'}(t)|^{2} dt \\ &\approx \|s_{m}(\tau)\|^{2} + \|s_{m'}(\tau)\|^{2} - \underbrace{2\mathcal{R}\left\{\int_{0}^{\tau} s_{m}(t)s_{m'}^{*}(t) dt\right\}}_{\approx 0}, \end{split}$$

where, subject to a maximal-power constraint, each $s_m(\tau)$ satisfies (cf. Eq. (2)):

$$||s_m(\tau)||^2 = \int_0^{\tau} s_m(t) s_m^*(t) dt \le nPT$$
 for all $m = 1, \dots, M$,

where $\mathcal{R}\{\cdot\}$ denotes the real part of a complex number and $(\cdot)^*$ is the complex conjugate. A decoder able to make correct decisions before the end of the transmitted symbol reduces the signaling delay. Furthermore, (11) shows that the decoder aims to detect the message using less signal energy than stated in the right-hand-side bound of (2).

The orthogonality of an OFDM transmission depends on the space between subcarrier. This space must be equal to 1/T. As mentioned above, the proposed early detection scheme makes

a sequential decision before the end of the symbol duration T. As a consequence, the orthogonality of the signals is not preserved, and the distance between two OFDM signals becomes nonlinear. Therefore, to reduce latency and preserve the orthogonality through the proposed early-detection scheme, $d_{mm'}^2$ must be linear for all $m \neq m'$ in an arbitrary codebook. An efficient solution to linearize these distances is to employ a precoding random matrix, in particular, a Hadamard transform, which renders the early-detection scheme feasible over OFDM [14].

III. OPTIMAL LATENCY IN ONE-HOP COMMUNICATION OVER AWGN CHANNELS

Consider a channel code with a blocklength of n channel uses, and with a symbol duration T. A decoder that makes its decision at the end of a transmitted symbol has latency:

$$L = nT. (12)$$

In this work, we consider a transmission with a fixed duration, but where the receiver operates at $\tau \in [0,T]$. Therefore, we are concerned by the minimal average $\mathbb{E}\left[\tau\right]$ needed to decode one of the M possible messages for a targeted BLER ϵ .

A. On Minimal Latency using an Optimal Stopping-Time Rule

The optimal average latency can be achieved through a genie-aided detector, i.e., a perfect error-detecting code is assumed [14]. Consider a sequential test characterized by:

$$\tau = \inf\left\{t : P(m|\mathbf{Y}_{\tau}) > S_m\right\},\tag{13a}$$

$$\delta = \hat{m}$$
, where $\hat{m} = \underset{1 \le m \le M}{\arg \max} P(m|\mathbf{Y}_{\tau})$, (13b)

where the stopping time τ is the minimal time in which the decoder has made a decision when $s_m(t)$ was transmitted, and δ is the final decision rule. The decoder makes its decisions as soon as the posterior probability reaches a predetermined threshold S_m . The probability of having a correct decision given a message m is denoted by $p(\tau|s_m(t))$. Since τ is a random variable, the average latency is:

$$\mathbb{E}\left[\tau\right] = \frac{1}{M} \sum_{m=1}^{M} \mathbb{E}\left[\tau | s_m(t)\right], \qquad (14)$$

where $\mathbb{E}\left[\cdot\right]$ is the expectation value. Assuming the message has a uniform distribution, the conditional average of τ given M=m is provided by:

$$\mathbb{E}\left[\tau|s_m(t)\right] = \int_0^T \tau p(\tau|s_m(t))d\tau. \tag{15}$$

Similarly, the probability of having a correct decision at a given τ for an (n, M, ϵ) -code is given by:

$$p(\tau) = \frac{1}{M} \sum_{m=1}^{M} p(\tau | s_m(t)).$$
 (16)

In an optimal early-detection scheme the average BLER must be:

$$\epsilon = 1 - \int_0^T p(\tau)d\tau. \tag{17}$$

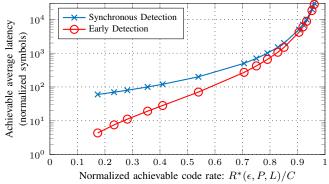


Fig. 1. Optimal achievable latency in one-hop communications. The BLER $\epsilon=10^{-12}$, and the SNR link budget is of 5 dB.

B. Minimal Latency of Channel Codes in the Finite Block-Length Regime over AWGN Channels

For synchronous detection, the minimal latency can be obtained for an (n,M,ϵ) -code by taking the minimum blocklength n needed to achieve a required ϵ given $k=\log_2 M$ information bits and a code rate R. Using the maximum achievable code rate given by Theorem 1, the minimum blocklength $n(\epsilon,\log_2 M)$ can be approximated by:

$$n(\epsilon, \log_2 M) \approx \left(\frac{Q^{-1}(\epsilon)}{C - R^*(\epsilon, n)}\right)^2 V,$$
 (18)

and the latency given by $L_{SD} = n(\epsilon, \log_2 M)T$.

In order to derive the minimal latency of an optimal early-detection scheme, let $\epsilon(\tau)$ be the BLER as a function of τ . From Theorem 1, it can be expressed as:

$$\epsilon(\tau) \approx Q \left(\frac{C(\tau) - R + \frac{1}{2n} \log_2 n}{\sqrt{V(\tau)/n}} \right),$$
 (19)

where $C(\tau)$ and $V(\tau)$ are functions of $P\tau$. By letting $\epsilon(\tau-\delta\tau)$ and $\epsilon(\tau)$ be the average BLER when decisions are made at $\tau-\delta\tau$ $\forall \delta\tau>0$ and τ respectively, where $\epsilon(\tau-\delta\tau)\geq \epsilon(\tau)$, the probability of having a correct decision at τ is:

$$p(\tau) = (1 - \epsilon(\tau)) - (1 - \epsilon(\tau - \delta\tau))$$
$$= \epsilon(\tau - \delta\tau) - \epsilon(\tau).$$

By letting $\delta \tau \to 0$, the distribution of τ is equal to the differential of the BLER:

$$p(\tau) = -d\epsilon(\tau). \tag{20}$$

The optimal average latency for this early-detection scheme can be computed by taking the expectation value for a given blocklength n and code rate R using (20). Thus, the optimal average latency in an early-detection scheme is $L_{\rm ED} = n \mathbb{E} \left[\tau \right]$.

Fig. 1 shows results on the minimal latency in one-hop communications using either synchronous detection or an optimal early detection at any fixed normalized achievable code rate. These results are for a targeted BLER $\epsilon=10^{-12}$ and an SNR link budget of 5 dB, and latency is expressed in terms of normalized symbols (L/T). The proposed early-detection scheme is shown to have lower latency than synchronous

detection as the decoder makes a reliable decision before the end of the transmitted symbols. The early-detection scheme is also shown to loose its advantage over synchronous detection as the channel codes operate near capacity. Therefore, such a scheme is more efficient for short messages.

In the following, we show that our findings can be applied to typical multi-hop scenarios where short messages are used.

IV. OPTIMAL LATENCY FOR LOW-TRAFFIC MULTI-HOP SYSTEMS

In time-sensitive applications, radio devices require time-synchronized low-latency services [13]. We apply the early-detection strategy for low-traffic multi-hop systems by retransmitting short messages as soon as they are correctly decoded. Consider h hops that employ a DF relaying scheme with synchronous detection where messages with latency L (as provided by (12)) are transmitted. Latency is defined as:

$$L_{\text{SD-DF}} = Lh. \tag{21}$$

If a relay makes correct decisions before the end of the transmitted symbol using an early-detection scheme and retransmits the message as soon as possible, latency is reduced.

Theorem 2: In low-traffic multi-hop systems, the minimal latency of DF relaying schemes using early-detections is:

$$\mathbb{E}\left[L_{\text{ED-DF}}\right] \le L_{\text{SD-DF}}.\tag{22}$$

Proof: Assuming that the h DF relays employ an (n, M, ϵ) -code along with an optimal early-detection scheme, if a source transmits an arbitrary message to a relay R_ℓ with a decoder that satisfies (9) at τ as in (13), the hop will retransmit the message through an OFDM-like signal to the next hop with lower latency than a scheme with synchronous detection.

In order to calculate the overall latency for h hops, we consider a source S that transmits an arbitrary message encoded by an (n,M,ϵ) -code, where latency $L_0=nT$. Next, a relay R_1 performs an optimal early-detection scheme, by which the decision has been made at $\tau_1 \leq T$. Therefore, the signaling delay is $L_1 = L_0 + \tau_1 n$, and so on. Assuming an i.i.d. random sequence $\tau_1, \cdots, \tau_h \leq T$ that satisfies (13), the overall average latency for h hops is:

$$\begin{split} L_{\text{ED-DF}} &= L_0 + \tau_1 n + \tau_2 n + \ldots + \tau_{h-1} n \,, \\ \mathbb{E}\left[L_{\text{ED-DF}}\right] &= nT + \mathbb{E}\left[\sum_{i=1}^{h-1} \tau_i n\right] \\ &= nT + (h-1)n\mathbb{E}\left[\tau\right] \leq hnT \\ &\leq L_{\text{SD-DF}} \,. \end{split}$$

The above proves that early-detection schemes can reduce latency in multi-hop systems using DF relaying schemes. ■

V. OPTIMAL LATENCY FOR PHASED CONTINUOUS-TRANSMISSION MULTI-HOP LINKS

Vehicle-to-vehicle or machine-to-machine multi-hop links are generally non synchronous, resulting in greater latency. However, assuming continuous transmission with variable-length blocks, a relay that would retransmit correct short

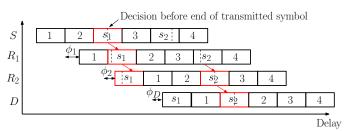


Fig. 2. Phased continuous-transmission multi-hop links using early-detection schemes. 1, 2, \cdots denotes the queued traffic, ϕ_i additional delays due to non-synchronous multi-hop links, and s_x short message blocks. Blocks in red designate retransmissions ahead of queued traffic.

messages ahead of queued traffic would reduce latency. Fig. 2 illustrates the proposed strategy. Assuming a random phase ϕ_i at each hop due to non-synchronous links between hops, the total average latency for DF-relaying schemes with synchronous detection is:

$$L_{\text{CTSD}} = \mathbb{E}\left[\sum_{i=1}^{h} \phi_i nT + \sum_{i=1}^{h} nT\right]$$
$$= (\mathbb{E}\left[\phi\right] + 1) L_{\text{SD-DF}}.$$
 (23)

For DF-relaying using an optimal early-detection scheme, the overall average latency is given by the following theorem.

Theorem 3: For phased continuous-transmission multi-hop links using a DF-relaying scheme with a random phase ϕ_i at each hop, the optimal average latency is bounded by:

$$\mathbb{E}\left[\phi\right] L_{\text{SD-DF}} \le L_{\text{CTED}} \le \mathbb{E}\left[\phi\right] L_{\text{SD-DF}} + \mathbb{E}\left[L_{\text{ED-DF}}\right]. \tag{24}$$

Proof: Assuming that the random phase ϕ and the time needed to make a correct decision τ are independent, this theorem is the immediate consequence of Theorem 2 and of (23). The lower bound in (24) implies that all the relays made their decision before the phase ϕ . The minimal average latency L_{CTED} is equal to its upper bound if all relays made their decisions after the phase. The upper bound in (24) is itself upper bounded by (23).

Therefore, in phased continuous-transmission multi-hop links, the use of early detection can reduce latency.

VI. RESULTS AND DISCUSSION

In this section, we present results for both low-traffic multihop systems and for phased continuous-transmission multi-hop links. The proposed optimal early-detection scheme is compared to synchronous detection for various (n,M,ϵ) -codes. We compute the exact optimal latency for low-traffic multihop systems with relays that employ an optimal early-detection scheme via Theorem 2, and we do the same for phased continuous-transmission multi-hop links via Theorem 3. As in Section III-B, the average latency is expressed in terms of normalized symbols.

Fig. 3 shows the optimal achievable average latency for various information blocksizes of both phased continuous-transmission multi-hop links and low-traffic multi-hop systems. Results are for 10 hops, an SNR link budget per hop of 5 dB, a BLER $\epsilon=10^{-12}$, and the random phase

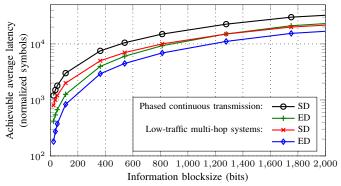


Fig. 3. Optimal achievable average latency of phased continuous-transmission multi-hop links and of low-traffic multi-hop systems using either synchronous detection (SD) or early detection (ED). The number of hops h=10, the BLER $\epsilon=10^{-12}$, and the SNR link budget is of 5 dB.

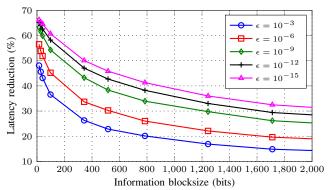


Fig. 4. Latency reduction for phased continuous-transmission multi-hop links using an optimal early-detection scheme with various BLERs ϵ . The number of hops h=4, and the SNR link budget is of 5 dB.

 ϕ is assumed to be uniformly distributed over [0,1], thus $\mathbb{E}\left[\phi\right]=1/2$. As expected, the latency is shown to increase with the information blocksize. More importantly, compared to synchronous detection, the proposed early-detection scheme shows an improvement in latency in both multi-hop scenarios.

The proposed early-detection scheme can significantly reduce latency, especially for short codes with a very-small BLER ($\epsilon \to 0$). Fig. 4 shows the latency reduction for various BLERs ϵ and information blocksizes with a fixed number of hops h=4 and an SNR link budget of 5 dB. The latency reduction is calculated as $100 \times (1-\frac{L_{\text{CTED}}}{L_{\text{CTSD}}})$. Compared to synchronous detection, it can be seen that the proposed early-detection scheme offers a latency reduction in the range of 20% to 65%. For any fixed BLER ϵ , codes with a smaller information blocksize have the most significant latency reduction. For a fixed information blocksize, a smaller BLER ϵ leads to greater latency reduction.

Fig. 5 shows the latency reduction for various normalized achievable code rates and SNR link budgets, where the number of hops h=4 and the BLER $\epsilon=10^{-12}$. It can be seen that the proposed early-detection scheme is particularly suitable for short blocklengths as the latency reduction diminishes as the code rate tends to capacity. Lower-rate codes benefit the most, with a latency reduction that culminates at little over

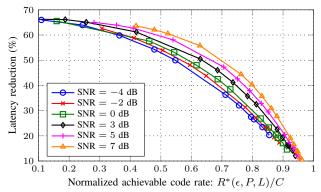


Fig. 5. Latency reduction for normalized achievable code rates with various SNR link budgets. The number of hops h=4, and the BLER $\epsilon=10^{-12}$.

65%. Fig. 5 also shows a latency reduction well above 40% over a very-large range of code rates, especially if the SNR budget link per hop can be increased.

VII. CONCLUSION

In this work, we described a strategy for one-hop and linear multi-hop systems with short messages that provably reduces latency without compromising reliability. The key element is an early-detection scheme based on a sequential-test technique where short messages are detected and retransmitted before being completely received, and where the test threshold ensures a targeted error probability. Compared to decode-and-forward relays that use synchronous detection, we have proved that the proposed scheme has the lowest overall latency for short messages. In addition, our results showed that over continuoustransmission links, the overall latency of the proposed scheme can be reduced by up to 66% while maintaining a block-error rate as low as 10^{-15} . The proposed early-detection scheme offers promising results over the AWGN channel, where it was shown to be suitable for ultra-reliable and extremely low-latency communications. Lastly, extending the proposed scheme to fading channels would be of interest for future work.

REFERENCES

- [1] M. Karzand and L. R. Varshney, "Communication Strategies for Low-Latency Trading," in *IEEE Int. Symp. on Inf. Theory (ISIT)*, 2015.
- [2] X. Yang, L. Liu, N. Vaidya, and F. Zhao, "A vehicle-to-vehicle communication protocol for cooperative collision warning," in *The First Ann. Int. Conf. on Mobile and Ubiquitous Systems: Netw. and Services*, 2004.
- [3] C. E. Shannon, "A Mathematical Theory of Communication," *Bell Syst. Tech. J.*, vol. 27, no. 3, pp. 379–423, 1948.
- [4] G. Durisi, T. Koch, and P. Popovski, "Toward Massive, Ultrareliable, and Low-Latency Wireless Communication With Short Packets," *Proc. IEEE*, vol. 104, no. 9, pp. 1711–1726, Sep. 2016.
- [5] J. Oestman, G. Durisi, E. G. Stroem et al., "Low-latency Ultra-Reliable 5G Communications: Finite-Blocklength Bounds and Coding Schemes," in *Int. ITG Conf. on Systems, Commun. and Coding (SCC)*, Feb. 2017, pp. 1–6.
- [6] N. Wen and R. A. Berry, "Reliability Constrained Packet-sizing for Linear Multi-hop Wireless Networks," in *IEEE Int. Symp. on Inf. Theory* (ISIT), 2008.
- [7] A. Chaaban and A. Sezgin, "When can a relay reduce end-to-end communication delay?" in *Int. Conf. on Commun., Signal Process., and Their Appl.*, 2015.
- [8] —, "Multi-Hop Relaying: An End-to-End Delay Analysis," IEEE Trans. Wirel. Commun., vol. 15, no. 4, pp. 2552–2561, 2016.

- [9] H. Q. Ngo and E. G. Larsson, "Linear Multihop Amplify-and-Forward Relay Channels: Error Exponent and Optimal Number of Hops," *IEEE Trans. Wirel. Commun.*, vol. 10, no. 11, pp. 1536–1276, 2011.
- Trans. Wirel. Commun., vol. 10, no. 11, pp. 1536–1276, 2011.

 [10] I. Maric, "Low Latency of Communications," ArXiv E-Prints, 2013.

 [Online]. Available: https://arxiv.org/abs/1302.5662
- [Online]. Available: https://arxiv.org/abs/1302.5662
 [11] G. Fettweis, M. Krondorf, and S. Bittner, "GFDM Generalized Frequency Division Multiplexing," in *IEEE Veh. Technol. Conf.*, 2009, pp. 1–4.
- pp. 1–4. [12] G. Wunder, P. Jung, M. Kasparick *et al.*, "5GNOW: Non-Orthogonal, Asynchronous Waveforms for Future Mobile Applications," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 97–105, 2014.
- [13] F. Schaich, T. Wild, and Y. Chen, "Waveform Contenders for 5G -Suitability for Short Packet and Low Latency Transmissions," in *IEEE Veh. Technol. Conf.*, 2014.
- [14] M. Au and F. Gagnon, "On Optimal Latency of Communications," ArXiv E-Prints, 2016. [Online]. Available: https://arxiv.org/abs/1610.00017
- [15] A. J. Viterbi, "The effect of sequential decision feedback on communication over the Gaussian channel," *Inf. Control*, vol. 8, no. 1, pp. 80–92, 1965
- [16] Y. Polyanskiy, H. V. Poor, and S. Verdù, "Channel Coding Rate in the Finite Blocklength Regime," *IEEE Trans. Inf. Theory*, vol. 56, no. 5, pp. 2307–2359, 2010.