A Transmission Scheme Based on Uniform Shortening LDPC Codes for Performance Improvement in Faster-Than-Nyquist Systems

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ABSTRACT Faster-than Nyquist (FTN) signaling is a research topic that has been drawing increased attention due to its capability of improving transmission speed without the need of extra bandwidth. However, the deployment of FTN signaling introduces inter-symbol interference (ISI) which severely degrade system performance. Interestingly, even without ISI equalizer, it has been recently shown that the joint application of LDPC codes with FTN signaling can exhibit rather good performance. To further improve the performance of LDPC codes over FTN systems, a transmission scheme that utilizes uniform shortening LDPC codes is proposed in this paper. It was found that their shortening counterpart can provide a coding gain at least 0.4 dB over a wide range of FTN factors compared with FTN systems that employ conventional LDPC codes. Moreover, using LDPC coded ISI-free system as the benchmark, the proposed transmission scheme can possibly provide 43% improvement in data rate with rather small performance degradation.

INDEX TERMS Faster-than-Nyquist signaling, LDPC codes, coded FTN systems, shortening.

I. INTRODUCTION
The phenomenon in which one transmitted symbol interferes with consecutive symbols is called inter-symbol interference (ISI). ISI causes a distortion at transmitter and receiver then suffers a much higher error rate. It is known that if a pulse shaping, i.e., the process of converting symbol to electrical signal, satisfies the first Nyquist criterion, ISI-free transmission can be achieved. Therefore, the signal processing at transmitter is practically implemented according to this criterion. Typically, models and simulations used in communication research are also assumed this criterion. Note that the communication systems that obey the first Nyquist criterion is referred to as Nyquist system. We also note that the distance between adjacent transmitted pulses for this system is normalized to be 1.

Faster-than-Nyquist (FTN) signaling is a promising transmission technique that violates the first Nyquist criterion. This technique has recently drawn considerable attention since it can provide higher transmission speed without bandwidth expansion [1]. FTN signaling can maximally reduce the distance of Nyquist system to approximately 0.802 without performance loss [2]. Note that the improvement of symbol rate provided by FTN signaling can be calculated from the reciprocal of the distance. So, FTN signaling can provide 1/0.802, i.e., about 25%, increase in symbol rate over the Nyquist system. However, ISI is unavoidably introduced by FTN signaling and this problem can be handled by employing ISI equalizer at receiver [3]–[5].

It is worth notable that the type of waveform for FTN signaling that allows 25% symbol rate improvement, as discussed earlier, is sinc pulse shaping [2]. Instead of using that kind of pulse shaping, it is reported that the use of root raised cosine (rRC) waveforms with FTN signaling can provide better performance [6]. This type of waveform can lower the distance from 0.802 to 0.703. Therefore, rRC waveform enables FTN systems to achieve about 43% data rate enhancement [7]. To the best of our knowledge, rRC pulse shaping is very popular for FTN signaling. So, this pulse is utilized to conduct almost the researches in this field [4], [5], [8]–[10]. Note that the improvement of symbol rates discussed here is ideal, i.e., theoretical upper bound for noiseless case with optimal receiver design.
For practical transmission systems, FTN signaling is not only corrupted by ISI but also the noise in communication channel. This problem is known to be solved by a technique called as channel coding. Thus, FTN system with channel coding is needed to ensure reliable transmission over noisy channels [7], [11]. The idea of applying FTN signaling with the powerful channel codes called low-density parity-check (LDPC) codes has been studied by many researchers [5], [12]–[15]. Recently, it is found that LDPC coded FTN system is very robust to both ISI and noise since this combination can achieve good BER performance without utilizing ISI equalizer [16]. Therefore, one benefit of applying LDPC code in FTN system is that its receiver can be implemented with low complexity. Additionally, for FTN systems, it has also been demonstrated that LDPC codes are more robust from ISI than polar codes [16].

It is intuitive to think that performance of LDPC coded Nyquist system is better than that of LDPC coded FTN system since the latter experiences ISI. For example, using LDPC coded Nyquist system as reference, the FTN system with LDPC code of rate 0.192 induces coding loss about 3 dB [16]. In order to improve the performance of LDPC coded FTN system, a transmission scheme based on FTN signaling and shortening LDPC codes is proposed in this paper. Normally, shortening techniques are used to construct rate-compatible codes [17] but in this work, it will be purposely utilized to combat ISI effect from FTN systems, which has never been studied in the literature before. We expected that the existence of known symbols incurred from shortening process can reduce the effect of ISI. The shortening LDPC codes used in this work are specifically constructed from the concept of uniform shortening distribution [18]. For the sake of simplicity, in this paper, we refer to this type of code as uniform shortening LDPC code. Our proposed transmission scheme employs the FTN systems with uniform shortening LDPC code. It is worth mentioning that pre-coding technique is the future research direction in this field and shortening technique can be thought as the utilization of pre-coding technique [19].

The paper is organized as follows. The basics and backgrounds are briefly introduced in Section II. The uniform shortening technique is explained in Section III. The proposed transmission scheme is presented in Section IV. Results and discussions are provided in Section VI. Finally, we draw the conclusions in Section V.

II. SYSTEM MODEL

The system model for FTN systems with LDPC codes is described in this section. Important parameters for both LDPC codes and FTN signaling are also introduced. Following [16], [19], the block diagram of the overall FTN systems with LDPC codes is shown in Fig. 1.

From the block diagram shown in Fig. 1, transmitter side comprises four main parts which are LDPC encoder, interleaver, modulation, and rRC shaping filter, respectively. The information vector \( \mathbf{m} \) of length \( k \) bits is the input of LDPC encoder. First thing to note is that \((n, k)\) LDPC code is defined by the sparse parity check matrix \( \mathbf{H} \) of size \((n - k) \times n\) where \( n \geq k \) and its code rate is given by \( R = k/n \). With this code definition, LDPC encoder transforms \( \mathbf{m} \) into the codeword vector \( \mathbf{c} \) of length \( n \) bits. Next, this codeword is then interleaved, so that the effect of burst error can be reduced. This process is represented in the figure by \( \Pi \). After that, the output \( \mathbf{b} \) from the interleaver is mapped into symbol vector \( \mathbf{a} \) via binary phase shift keying (BPSK) modulation. Finally, the FTN signal \( s(t) \), defined by rRC shaping filter, can be expressed as the summation of a sequence of modulated symbols,

\[
s(t) = \sqrt{E_s} \sum_{i=1}^{N} a_i h(t - i \tau T).
\]

The parameters involving in (1) are defined as follows. \( E_s \) is the energy of each symbol \( a_i \), \( h(t) \) represents the impulse response of pulse shaping filter. Symbol period is denoted by \( T \) and \( \tau \) is the FTN factor, also known as symbol packing ratio [19]. For our study, \( E_s \) and \( T \) are normalized to be 1. The rRC pulse is chosen for \( h(t) \). The characteristic of FTN signal \( s(t) \) is controlled by \( \tau \), i.e., \( 0 < \tau < 1 \), and \( \tau \) indicates the distance between adjacent waveforms. Note that a lower value of \( \tau \) corresponds to a higher transmission speed. An example of Nyquist signaling and FTN signaling with \( \tau = 0.82 \) and \( \tau = 1 \) (ISI-free) is demonstrated in Fig. 2. From this figure, it is obviously seen that the spacing between adjacent pulse of FTN system is shorter than Nyquist system. Thus, FTN signaling reduces the symbol period in order to increase the symbol rate. However, to achieve this benefit, there is a trade-off between transmission speed and the bit error rate performance. It can be seen in this figure that the transmitted symbols in FTN signaling are interfered with each other, i.e., ISI. With the presence of ISI, the performance degradation at receiver cannot be avoided. Typically, the ISI equalizer will be employed at receiver to minimize this effect [3], [4], [20].

Assuming that the FTN signal \( s(t) \) is transmitted through noisy channel and the received signal \( r(t) \) can be written as follows:

\[
r(t) = s(t) + w(t),
\]

where the noise signal \( w(t) \) is Gaussian distributed with zero-mean and variance of \( N_0/2 \). Noting that the transmitted FTN signal is affected by both random noise and ISI.
Next, the corresponding receiver for LDPC coded FTN signaling will be briefly described. At this side, matched filter, demodulation, deinterleaver, and LDPC decoder are four main components. The received signal \( r(t) \) is then matched-filtered by \( g(t) \) and the output \( y(t) \) can be expressed as [19]

\[
y(t) = r(t) * g(t) = \sqrt{E_s} \sum_{i=1}^{N} a_i t - i \tau T + \tilde{w}(t),
\]

where \( g(t) = \int h(x) h^*(x - t) dx \) and \( \tilde{w}(t) = \int w(x) h^*(x - t) dx \). Assuming perfect timing synchronization, the matched-filtered signal \( y(t) \) is sampled every \( \tau T \). The \( j \)th received sample is given by

\[
y_j = y(j \tau T) = \sqrt{E_s} \sum_{i=1}^{N} a_i (j \tau T - i \tau T) + \tilde{w}(j \tau T)
\]

\[
= \sqrt{E_s} a_0 g(0) + \sqrt{E_s} \sum_{i=1, i \neq j}^{N} a_i (j - i) \tau T + \tilde{w}(j \tau T).
\]

After that, BPSK demodulation produces soft output in terms of log-likelihood ratio. This output \( \tilde{b} \) is deinterleaved and then fed into the LDPC decoder. Finally, the decoder estimates the information vector \( \tilde{m} \).

### III. SHORTENING TECHNIQUE

As mentioned above, shortening is typically used to construct rate-compatible codes but in this work, it is used to formulate the proposed transmission scheme in order to achieve overall performance enhancement. Before going to describe our proposed transmission scheme, the basic concept of shortening is introduced in this section. Note that LDPC codes presented in the previous section will be used in this context.

By choosing code of rate \( R = k/n \) as the mother code, a mechanism of shortening at transmitter side is illustrated in Fig. 3. A group of information bits with length \( k_m \) bits and a group of known symbols with length \( k_s \) bits are used to form the information vector \( m \) of length \( k = k_m + k_s \) bits. One can think that \( k_m \) positions out of possible \( k \) positions of the information vector must be replaced by \( k_s \) known symbols. Unlike \( m \) defined in the previous section, it is important to state that \( m \) is now a combination between \( k_s \) known symbols and \( k_m \) information bits. Please note that the actual information is a group of \( k_m \) information bits. The values and positions of \( k_s \) known symbols are assumed to be known at both the transmitter and receiver. Next, LDPC encoder produces a codeword \( c \) from the modified information vector \( m \) in a regular manner. After that, all the known symbols must be removed before transmission. The actual codeword length is thus shortened to \( n_s = n - k_s \) and this is why we call this kind of code as shortening code. The actual code rate, which is always lower than \( R \), is given by \( R_s = k_m/n_s \), i.e., the ratio between actual information bits and actual codeword length. By controlling \( k_s \), a series of lower rate codes can be constructed from only a single mother code. Therefore, a rate-compatible code can be obtained via shortening technique.

The illustrative example for shortening LDPC encode is described here. By using \((6, 4)\) mother LDPC code, the construction of \((4, 2)\) shortening LDPC code is shown in Fig. 4. The input of LDPC encoder is modified information vector of length \( k = 4 \) bits, \( m = [m_1 m_2 m_3 m_4] \). The known symbols are inserted into the first and the third positions, \( m_1 \) and \( m_3 \). So, \( m_2 \) and \( m_4 \) are responsible for actual information bits. After getting the outputs from LDPC encoder, the known symbols are removed, and then actual codeword of length \( n_s = 4 \) is finally produced.

The corresponding signal processing to deal with shortening at receiver side is depicted in Fig. 5. After collecting \( n_s \) soft outputs from the deinterleaver, these \( n_s \) soft outputs must be technically combined with \( k_s \) soft outputs that represent \( k_s \) known symbols. After this combining, these \( n \) soft outputs are taken as the inputs of LDPC decoder and then the decoding is
proceeded in a regular manner. Finally, the $k_s$ known symbols will be ignored and the estimation $\tilde{m}$ of length $k_m$ bits is provided.

Note that all the soft outputs regarding known symbols remain constant throughout the decoding process so that these soft outputs can be considered as the perfect knowledge for the LDPC decoder. For example, if zero bit is selected as known symbols and the soft output is defined as $\ln(Pr(c_j = 1|y))/Pr(c_j = 0|y))$, where the terms inside natural logarithm are posterior probability [21], [22]. The value of soft output for known symbols can be -10 so that $Pr(c_j = 0|y)$ approaches to 1.

Generally, there are many shortening techniques provided in the literature [23], [24]. For shortening LDPC codes, the positions of $k_s$ known symbols that we have to choose before encoding directly affect the decoding performance [17], [18]. In order to achieve good performance, the shortening technique called uniform shortening distribution is utilized in this work. With this technique, the known symbols must be inserted to the specific positions so that each check node of LDPC Tanner graph is equally connected to the positions of known symbols, i.e., $k_s$ variable nodes that represent $k_s$ known symbols.

The example of the Tanner graph relating to (4, 2) shortening LDPC code constructed from this technique is shown in Fig. 6. From this figure, it can be seen that each check node is equally connected to known symbol, e.g., one known symbol for this case. Note that the distribution of variable nodes is optimized [25]. So, all check nodes can equally take the benefit from the perfect knowledge and this situation is regarded as uniform shortening distribution. We note before ending this section again that the shortening LDPC codes constructed with this technique is referred to in this work as uniform shortening LDPC codes.

IV. THE PROPOSED TRANSMISSION SCHEME

We remind the reader that the proposed transmission scheme is the joint application between FTN signaling and uniform shortening LDPC codes, explained in Section II and III, respectively. The block diagram for the proposed transmission scheme is very similar to the coded FTN systems displayed in Fig. 1. Two different points are as follows. At the transmitter side, the shortening LDPC encoder is performed instead of LDPC encoder while the LDPC decoder is replaced...
by shortening LDPC decoder at the receiver side. Therefore, the block diagram of this proposed transmission scheme can be represented by Fig. 7.

We believe that the known symbols involving in shortening process can be utilized to improve the performance of FTN systems. The reason for this is illustrated in Fig. 8. This figure shows the example of just one check node extracted from the whole Tanner graph of shortening LDPC codes. This check node connects to three variable nodes in which two of them are known symbols and the last one represents the actual information bit. Suppose that the leftmost variable node, used to represent the actual information bit, has very low reliability. From the figure, it is obviously seen that two incoming information, involving in the computation of extrinsic information for this low reliability variable node, are perfect knowledge. Therefore, one can expect that the extrinsic information can rapidly recover this low reliability node. Note that the structure shown in Fig. 8 or similar patterns can possibly arise.

Typically, we can construct uniform shortening LDPC code of rate $R_s$ from various mother codes of different rates $R > R_s$. For example, the mother codes, that can be used to construct (544, 272) uniform shortening LDPC code of rate $R = 1/2$, are listed in Table 1. From this table, it is observed that the more known symbols can be obtained at higher rate. It is expected that the greater amount of known symbols can provide the proposed transmission scheme with better decoding performance.

One may concern that the block length must be increased in order to get more number of known symbols and this may result in higher decoding complexity. However, it should be noted that almost computational complexity of LDPC decoding algorithm belongs to check node. Table 1 clearly shows that the number of check node, denoted by $n_c$, remains constant when the number of known symbols is increased. Note that the actual information bit length is defined by $k_o = k - k_s$. It is also worth mentioning that the LDPC decoding algorithm does not perform any calculation for variable nodes which represent known symbols since the information from these nodes is always the perfect knowledge. Therefore, the shortening technique can be utilized with negligible additional decoding complexity.

### V. RESULTS AND DISCUSSIONS

The BER performances of the proposed transmission scheme are presented in this section. The construction of LDPC code is based on the definition provided in 5G standard [26]. All the simulations are performed over BPSK-AWGN channels. The sum-product algorithm with 50 maximum iterations is used as the LDPC decoding. At the transmitter side, all known symbols are selected to be zero bit. The log-likelihood ratio for known symbols are fixed to be -10. Note that LDPC code intentionally designed for specific rate or non-shortening LDPC code is referred to as dedicated LDPC code. For comparison purpose, the performance of dedicated LDPC coded Nyquist system, i.e., asymptotic performance for ISI case, is used as the benchmark.

Before going to present the first result, we would like to emphasize about our main hypothesis again. It is curious to know that whether shortening technique can improve the decoding performance of LDPC coded FTN system. Over the FTN systems, it is shown in Fig. 9 that the performance of uniform shortening LDPC codes surpass that of dedicated LDPC codes. Therefore, as we expected, the proposed transmission scheme can be utilized to increase the robustness of LDPC coded FTN systems. However, not all the shortening techniques can offer the superior performance in the FTN systems. It is clearly seen that the BER performance of the proposed transmission scheme significantly outperforms that of random shortening LDPC codes. From the figure, we can

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**TABLE 1.** Various mother codes for constructing (544, 272) shortening LDPC code.

| Rate | $n$  | $k$  | $k_s$ | $n_c$ | $k_o$ |
|------|------|------|-------|-------|-------|
| 2/3  | 816  | 544  | 272   | 272   | 272   |
| 3/4  | 1088 | 816  | 544   | 272   | 272   |
| 4/5  | 1360 | 1088 | 816   | 272   | 272   |
| 5/6  | 1632 | 1360 | 1088  | 272   | 272   |

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**FIGURE 10.** Performance comparison between the LDPC coded FTN system with equalizer and the proposed transmission scheme without equalizer. The block length of these figures are 512 bits and the code rate are 1/2.
FIGURE 11. Performance of the proposed transmission schemes constructed from different mother codes. The upward-pointing triangle, circle, and asterisk markers indicate the proposed transmission scheme constructed from mother codes with $R = \frac{5}{6}$, $\frac{3}{4}$, and $\frac{2}{3}$, respectively. The solid lines show the proposed transmission scheme with $\tau = 0.8$, $R_s = \frac{1}{2}$, and $n = 2176$ bits. Similarly, the dashed lines represent these schemes with $\tau = 0.8$, $R_s = \frac{1}{2}$, and $n = 544$ bits whereas the dotted lines refer to these schemes with $\tau = 0.7$, $R_s = \frac{2}{3}$, and $n = 264$ bits.

FIGURE 12. Performance of the proposed transmission schemes with various $\tau$. The block length for this figure is 544 bits and the code rate is $1/2$.

FIGURE 13. Performance of the proposed transmission schemes with various $\tau$. The block length for this figure is 4224 bits and the code rate is 1/2.

TABLE 2. The trade-off between the transmission speed and performance loss from using the proposed transmission schemes.

| $\tau$ | Speed Improvement from FTN Signaling | Performance Loss (dB) |
|--------|-------------------------------------|-----------------------|
| benchmark |  | \begin{tabular}{l|l|l}  \\[-2pt]  LDPC Coded FTN Systems & The Proposed Transmission Schemes \\[-2pt] \end{tabular} |
| 0.9 | +11% | 0.2 (0.6) | 0.3 (0.3) |
| 0.8 | +25% | 0.5 (0.5) | 0.3 (0.5) |
| 0.7 | +43% | 1.5 (1.4) | 0.8 (1.4) |
| 0.6 | +67% | 2.5 (2.2) | 1.5 (2) |
| 0.5 | +100% | 2.5 (3.1) | 2.4 (3) |

For the rightmost column, the performance comparison between benchmark (3S-free case) and our proposed transmission scheme (3S case). The values represent the loss from $n = 4224$ bits whereas the values inside parentheses belong to $n = 544$ bits.

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see that the random shortening LDPC codes cannot outperform the dedicated LDPC codes.

Figure 10 shows the performance comparison between the LDPC coded FTN system with equalizer and our proposed scheme without equalizer. The experiments are conducted for three FTN factors, $\tau = 0.9$, 0.8, and 0.7. It has been observed that the employing of equalizer cannot improve the bit error rate performance at $\tau = 0.9$. Note that this observation is identical to the result given in [15]. So, if $\tau \geq 0.9$, it can be stated that there is no benefit of using equalizer in LDPC coded FTN system. However, it can be also noticed from the figure that equalizer can improve the performance of LDPC coded FTN system. The joint application of equalizer and shortening LDPC codes for FTN systems will be further explored in our future work.

Next, the effect of choosing different rate of mother codes $R$ on the performance of the proposed transmission scheme is considered. Note that the different rates $R$ yield different number of known symbols, as demonstrated in Table 1. In order to observe this effect, the simulations of various proposed transmission schemes constructed from different mother codes are therefore conducted. As we expected, it is founded from Fig. 11 that the best performance of the proposed transmission schemes can be achieved from the mother code of $R = \frac{5}{6}$, i.e., the highest rate for this case. Therefore, a higher number of known symbols tend to provide the better performance for our proposed transmission scheme. With this evidence, the mother code of $R = \frac{5}{6}$ will be utilized for all following simulations.

Note again that the transmission speed of FTN system can be controlled through the FTN factor $\tau$. So, the simulations of the proposed transmission scheme over wide range of $\tau$
are executed and their performances are shown in Fig. 12 and Fig. 13. The benchmark performances are included in order to show the advantage of our proposed transmission schemes. The FTN factor $\tau$ is varied from 0.9 to 0.5 so that the transmission speed is increased from 11% to 100%. It can be observed from the figure that the BER performance of the proposed transmission scheme degrades, as $\tau$ increases. The trade-off between the transmission speed and performance loss from using the proposed transmission schemes is summarized in Table 2. Interestingly, with the penalty of 1 dB, the proposed transmission scheme with $n = 4224$ bits can significantly improve the transmission speed up to 43%. Moreover, at $\tau = 0.9$, this speed improvement can be achieved with negligible performance loss. Thus, the proposed transmission scheme is a promising candidate for modern communication systems in which the FTN signaling can be applied, e.g., 5G cellular backhaul or visible light communications [19].

VI. CONCLUSION

FTN signaling is the emerging transmission technique for modern and future communication systems that demand higher data rate. In this work, we propose the first transmission scheme based on FTN signaling and shortening LDPC codes which can be utilized to improve the system performance. Over a wide range of FTN factors, i.e., $\tau \geq 0.7$, it has been demonstrated in this work that the proposed transmission schemes are able to provide excellent BER performance together with significant data rate improvement, e.g., up to 43%. For lower values of $\tau$, it is quite challenging to design coded FTN systems and this topic will be explored as future work. Furthermore, for FTN systems, shortening techniques could be regarded as pre-coding techniques which is expected to be one of the research trends in this field.

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