An Adaptive TDD Network with Network Coding
Embedded Two-way Relay

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Abstract

Using relays to receive and forward packets between a network base station and network users is a promising solution to address the cellular coverage issue. In this paper, we consider time division duplexing (TDD) networks and explore the use of network coding for implementing the relays. Several transmission scenarios are investigated, including direction transmissions, one-way relay and two-way relay. In addition, we propose an adaptive TDD network, which enables the network to adaptively configure frame structures based on channel conditions to support direct transmissions, cooperative relay and two-hop relay (one-way and two-way). An opportunistic decoding scheme and a relay operation scheme are introduced to realize the proposed adaptive TDD network in a distributed manner. Both throughput and outage probability are derived. Performance evaluations show that the proposed adaptive TDD network based on network coding achieves the maximum throughput, as compared with one-way relay (without network coding), and extends the cell coverage range (compared with direct transmissions).

Index Terms

TDD, superframe configuration, relay, network coding, adaptive, throughput, outage.

I. INTRODUCTION

In the advanced communications, such as Long Term Evolution (LTE) [1]-[4], the multiple-input and multiple-output (MIMO) and orthogonal frequency division multiplexing (OFDM) techniques are adopted to combat wireless channel fading to increase the link throughput. However, both MIMO and OFDM do not inherently mitigate cochannel interference and therefore they fail to benefit the cell edge users [5]. One possible solution for this issue is to use relays between base stations and network users to receive and forward messages [6][7].

Relaying, including cooperative relaying, dual-hop relaying [8], and multi-hop relaying [9][10], is an extensively investigated technique in wireless communications to address some specific network performance issues. A cooperative relay is used to assist the data transmissions of a weak communication pairs which may involve the edge of a communication coverage area. Several cooperative relaying Medium Access Control (MAC) protocols have been introduced based on the IEEE 802.11 standard [11][12]. Considering
the next generation LTE networks, cooperative relaying has a potential to be utilized to improve the network throughput. Dual-hop and multi-hop relays usually are used to receive and forward the communication data for communication pairs which do not have direct transmission links. With the assistance of the dual-hop or multi-hop relays, the network coverage can be increased significantly. Typically, a relay can operate in either a half-duplex or full-duplex mode. Due to the significant difference in the power level of incoming and outgoing signals, the full-duplex relay is generally considered as impractical and thus the half-duplex relay is more commonly used in wireless communication networks [13]. However, a half-duplex relay requires two channels in terms of time/frequency to relay a received signal, which halves the network maximum/peak throughput. To address this issue, two-way relays have been proposed by using physical network coding, which enables a relay station to relay two signals in two channels [14].

Network coding was first introduced in satellite communications [15] and then developed for wired networks [16]. Currently, network coding is a promising technique for wireless networks with relays. In [17], a network coding scheme for two-user cooperation is proposed. In this scheme, each network user first transmits its own message and then a binary addition of its own and its partner’s messages is transmitted. The idea of this two-user network coding scheme is then used in two-way relay [18]. In the relay, a base station and a network user are considered as two cooperative users. A downlink and an uplink message coming from the base station and network user respectively are received by the relay first and then a coded message is sent to both the base station and network user.

In the LTE, the time division duplexing (TDD) and frequency division duplexing (FDD) have been defined as the two operation modes. In TDD, a communication channel (a set of orthogonal sub-channels) is divided into different time slots (subframes) which are then allocated to uplink and downlink transmissions according to traffic requirements. In this manner, a common carrier is shared between the uplink and downlink and the channel resource is switched in time. However, in FDD, two different channels are used for uplink and downlink transmissions. In this paper, we consider a TDD network scenario and investigate TDD subframe configurations and algorithms to support relay to achieve a higher network throughput and a larger coverage range. Our contributions are summarized as follows.

a). We introduce the relaying technique into a TDD network by considering dynamically configure the TDD superframe base on channel measurement report sent by network user in the uplink. One-way relaying and network coding based two-way relaying methods are both introduced in the TDD network. Considering a Rayleigh fading environment, the related throughput and outage performance are evaluated for the TDD network.

b). We propose an adaptive TDD network, which is able to adaptively configure its superframe structure based on the channel/link condition to support direct transmissions, cooperative relaying and dual-hop
relaying (one-way or two-way relay). Through this adaptive subframe configuration, a transmission pair, i.e., a base station and a network user, can adaptively schedule their downlink and uplink transmissions. The network throughput and outage performance for the proposed adaptive TDD network are also evaluated in this paper.

c). An opportunistic decoding scheme for receivers and an operation scheme for relays are proposed in this paper. By implementing these two schemes in the proposed adaptive TDD network, the receivers and relays can be implemented in a fully distributed manner without any feedback between a base station and a network user.

d). Case studies in vehicular network are presented and the improved throughput and outage performance are shown in this paper.

The remainder of this paper is organized as follows. In Section II, we introduce the general network model and the conventional superframe configuration without supporting relays is explored. We also present the TDD subframe configuration method for supporting the one-way relay. In Section III, the network coding based two-way relay is presented for the TDD network. We propose an adaptive TDD network to support direct transmissions, cooperative relaying and two-hop relaying. Moreover, an opportunistic decoding scheme for receivers and a relay operation scheme are proposed to implement this adaptive TDD network in a distributed manner. Section IV derives the closed-form network throughput and outage probability expressions. The numerical performance results are presented in Section V. Section V also presents the network performance considering an application of this adaptive TDD network to vehicular networks. Finally, Section VI summarizes this paper and gives the conclusion.

II. NETWORK MODEL

A. Network Topology

In this paper, we consider a network as shown in Fig. 1. In the model, a base station is located in the center of a cell while network users are randomly located around the base station, which may be either within the cover range or beyond the cover range of the base station. We assume that the network is operating in TDD mode. For each base station-user communication pair, we assume a channel (i.e., a set of orthogonal sub-channels in OFDM) is assigned and exclusively used by this communication pair. Meanwhile, each network user may also operate as relay for other network users which are served by the same base station.

In Fig. 1, three scenarios of network users are illustrated. The first scenario, User 1, represents some network users which have a good coverage and thus have a reliable direct communication link with the base station. The second scenario, User 2, represents some network users which are located at the cell
edge and the direct communication links are weak and, therefore, cooperative relays are recommended for such communication pairs to assist their transmissions. In the third scenario, User 3, is located beyond the cover range of the base station or has a very bad coverage from the base station and, therefore, it does not have a direct communication link with the base station. In this case, a dual-hop relay is needed in the communication pair to help the base station/network user to relay its communication packets. The relay in this figure is also a network user which is able to successfully decode the received packets for the peer network users in downlink transmissions or base station in uplink transmissions.

![Network model](image)

Fig. 1. Network model

**B. Conventional Superframe Configuration**

We assume every superframe is 10 ms in length and is further divided into 10 subframes with equal length as shown in Fig. 2. In conventional superframe configuration, the 10 subframes are then allocated for uplink transmissions and downlink transmissions based on the traffic load and requirement, which means more subframes will be assigned for uplink/downlink transmissions if the user has more traffic in uplink/downlink traffic. We assume the network is able to dynamically change the superframe configuration at every superframe. The relaying subframes are not available in the conventional superframe configuration due to the reason that the subframes are only allocated for direct uplink and downlink transmission.

**III. Adaptive Superframe Configuration for Relaying**

**A. Superframe Configuration with Basic One-way Relay**

In a one-way relay, a relay user transmits in one direction at a time, which implies that the relay can only receive and forward the uplink or the downlink traffic for a communication pair. In a TDD network,
both uplink and downlink use the same frequency channel and the channel access time is divided into superframes. Each superframe contains a group of subframes which are assigned for uplink and downlink transmissions.

Considering one-way relays in the uplink and downlink transmissions, a basic superframe configuration is shown in Fig. 3. In the figure, Fig. 3(a), a superframe contains several subframes which are assigned for downlink and uplink transmissions according to the traffic requirements. For the purpose of enabling relay transmissions, i.e., cooperative relay or dual-hop relay, each subframe is further divided into two equal slots. We consider the first subframe for downlink as an example. In the first slot, a base station transmits a packet to its destination. Due to the channel condition, the destination receiver may not successfully receive the transmitted packet. Therefore, another network user which has successfully received the packet will use the second slot to forward the original base station transmitted packet to its destination network user. The two slots will be treated as two new subframes in the new superframe configuration as shown in Fig. 3(b).

This is a simple and straightforward approach to implement one-way relay in the TDD network. However, the aforementioned superframe configuration may halve the network maximum/peak throughput since each subframe is divided into two equal parts and the channel access time for uplink/downlink transmissions is halved. To improve the network throughput, we apply the network coding based two-way relay and the corresponding superframe configuration is introduced into the TDD networks.

B. Superframe configuration with network coding based two-way relay

In this subsection, we present a superframe configuration to support network coding based two-way relay as shown in Fig. 3(c). In the figure, we consider the same uplink-downlink traffic requirement as in the previous section. In two-way relay with network coding, the relay transmitted the coded packet for both uplink and downlink at the same time instead of relaying each uplink/downlink packet once at time,
which helps to save one time slots. To further improve the throughput, analog network coding [20] and physical layer network coding [21] are proposed by allowing relay to receive the uplink and downlink packet at the first time slot, and then transmit the coded packet at the second time slots. However, since the uplink and downlink share the same frequency channel and the uplink and downlink packets are transmitted at different slots in TDD network, we consider the most applicable three slots networking code relaying scheme. In the superframe configuration, for each uplink-downlink subframe pair, i.e., subframe 2 and subframe 3 in Fig. 3(a), it is divided into three time slots (treated as three subframes) with equal length as shown in Fig. 3(c), which are then assigned for uplink, downlink and two-way relay transmissions, respectively. For each individual uplink/downlink subframe which can not be bundled as an uplink-downlink pair with its neighbor subframes, i.e., subframe 1, a basic one-way relay configuration is used and the relay will transmit the packet at the relaying subframe (subframe 2). In the third and fourth subframes in Fig. 3(c), an uplink-downlink pair exists and the network coding based two-way relay will be applied to transmit the coded packet in the subframe 5. Moreover, in order to maintain the same uplink-downlink traffic ratio which is determined by the network user’s traffic load, the subframe length is configured flexible and all the subframes have the equal length after the superframe configuration for relaying, notice that the superframe length is fixed (e.g., 10 ms in TD-LTE). The relay operation process is shown in Fig. 4. The left part of Fig. 4 illustrates an example of the downlink one-way relay. In the figure, a downlink subframe is divided into two equal time slots. In the first time slot, the base station transmits a packet to the destination. At the same time, a relay also successfully receives the transmitted packet. Due to the channel condition, the destination network user may fail to decode the transmitted packet. Therefore, the relay will forward this packet in the second time slot. In the right part of Fig. 4, network coding based uplink-downlink two-way relay is illustrated. In the figure, a base station first sends a downlink packet in the first time slot and a relay successfully receives this packet and decodes it. However, the relay will not try to forward the downlink packet in the second time slot immediately. Instead, the second time slot is assigned to the network user for its uplink packet transmission. Meanwhile,
the relay also successfully receives and decode the uplink packet. Then the decoded downlink and uplink packets will be network coding coded by the relay. In the third time slot, the coded packet is transmitted by the relay in both base station and network user directions. Since both base station and network user have a cope of their previously transmitted packet, they are able to decode the relay transmitted packet and get the desired packet.

![Operation process of the one-way relay and two-way relay](image)

**Fig. 4.** Operation process of the one-way relay and two-way relay

### C. Adaptive TDD network frame configuration

The network coding based two-way relaying is introduced into TDD network in [19]. However, in [19], every subframe is split into three time slots in order to implement network coding based two-way relay, which assumes that both uplink and downlink transmissions happen within a same time slot and, therefore, two-way relay can be deployed. However, we are considering a TDD network that each individual subframe is only assigned for uplink or downlink transmissions, i.e., TD-LTE, splitting every single subframe will waste a lot of time resources. Moreover, splitting every subframe will degrade the throughput performance when the direct link is reliable. Therefore, adaptive network with relays has a higher throughput when the channel condition keeps changing since it is dynamically changing the superframe configurations by determine whether relays are needed or not based on the channel measurement report.

The adaptive network related to relay has been well studied for 802.11 WLAN networks [11][12]. In this subsection, we explore the adaptive network in the TDD network architecture and propose an algorithm to enable transmissions accommodating direct transmissions, cooperative relay transmissions and dual-hop relay transmissions. In the adaptive TDD network, the network operates in two modes, i.e., direct transmission mode and relay assist transmission mode (including one-way relaying and two-way relaying). The adaptive TDD network superframe configuration is divided into two phases. In the first phase, the uplink and downlink traffic is estimated and then the superframe is configured according to the uplink-downlink traffic requirement. In the second phase, the network periodically check the channel measurement report, i.e. CQI report in TD-LTE network, sent by the network user in the uplink, which
the network checks the channel measurement report by the network at the beginning of every superframe
  if the channel condition is good
    direct transmission mode is configured
    and conventional superframe configuration is selected
  else if the channel condition is bad or not receiving the measurement report
    relay assist transmission is configured
    and one-way relaying and two-way relaying subframes are allocated within a superframe
  broadcast the superframe configuration and restart this process at the beginning of next superframe

may be done at the beginning of each superframe or at the beginning of every several superframes in order to reduce the signaling and processing overhead. We assume the network is checking the measurement report and evaluating the channel conditions at the beginning of each superframe and the network is able to configure every superframe. After the channel evaluation is finished, a network operation mode will be chosen to complete the following superframe configuration. If the channel conditions between the network and the user is good enough (above a certain threshold), which means the direct link is reliable, the direct transmission mode will be selected and the conventional superframe configuration is applied. Otherwise, if the channel condition is below the threshold or the measurement report is lost in the uplink, the relay assist transmission mode will be selected. In this mode, the network will try to allocate subframes within every superframe to allow the relays perform relaying. When the network is allocating the relaying subframes, each uplink-downlink subframe pair is split into three time subframes for uplink, downlink and two-way relay transmissions. The remaining subframes (remainder of the superframes), which are not counted for uplink-downlink subframe pairs, will be split into two subframes for uplink/downlink and one-way relay transmissions. To maintain the same uplink and downlink traffic ratio, the slot lengths are then adjusted to have the equal length. The final superframe configuration parameters are send to the network user and also broadcast to all relays (other users within the same network). The operation of the adaptive superframe configuration is summarized in Table I.

To implement the proposed adaptive TDD network, an opportunistic decoding scheme is proposed and presented in Fig. 5. In Fig. 5, a receiver, which is a base station in uplink transmission or a network user in downlink transmission, is operating in relay assist transmission mode. In the decoding scheme, the receiver checks the frame configuration at the end of each subframe. If current subframe is a transmission subframe, i.e., downlink subframe for base station, or uplink subframe for a network user, the currently transmitted packet will be put into the three-packet buffer in the receiver. If current subframe is not
a transmission subframe, the receiver will attempt to receive a packet from the antenna. If the CRC checking of the received packet is successful, the packet will be put into the buffer. If the CRC checking fails, an null sequence will be put into the buffer. At the end of each relay subframe, all the packets, including successfully received packet, transmitted packet and null sequence, are fetched from the buffer. The receiver will check the number of the packets. If the number is two, which means that the relay is operating in an one-way relay mode and the relayed packet is a simple copy of the original received packet, the receiver will select the non null packet as an output. If the number is three, which means the relay is operating in two-way network coding mode and the relayed packet is the network coding coded packet for an uplink and a downlink packet, the receiver need to perform the decoding and select the desired packet.

Fig. 6 shows the operating scheme of a relay station. In the figure, a relay is assumed to receive a packet at the end of each uplink and downlink subframe. If the received packet passes the CRC checking, the packet will be put into the two-packet buffer. Otherwise, if the CRC checking fails or the relay does not receive a packet in the uplink/downlink subframe, a null sequence is put into the buffer. At the beginning of each relay subframe, the relay will fetch all packets from the buffer and count the number of packets. If the packet number is one and non null, which means that the relay should operate in one-way relay mode, the relay transmits a copy of this packet to its destination. Otherwise, if the packet number is two and non null, which means that the relay received an uplink and a downlink packet and the relay should operate in two-way network coding mode, the relay will perform network coding for these two packets and transmit it to both the base station and network user directions. If the any packet fetched from the buffer is a null packet, the relay will know errors happened in the receive packet and will discard all the buffered packet and not perform relaying during current relay subframe.

Fig. 5. Receiver opportunistic decoding scheme
IV. PERFORMANCE ANALYSIS

In this section, we investigate the performance of proposed adaptive TDD network with network coding based two-way relays.

A. Network Throughput

The normalized TDD network throughput, $S$, is expressed as the average successfully transmitted data bits (uplink plus downlink) in a TDD superframe calculated by the following equation,

$$ S = \frac{E[b]}{T}, $$

(1)

where $T$ is the length of a TDD superframe, $E[b]$ is the successfully transmitted data bits in a superframe. In direct transmissions, we assume that a TDD superframe contains $N$ subframes and $n$ blocks are transmitted in a subframe. Therefore, we get

$$ E[b] = nNB(1 - p_b)B, $$

(2)

where $B$ is block size and $p_b$ is the bit error rate of direct transmission link. Therefore, the network throughput in direct transmission, $S_d$, can be expressed as

$$ S_d = \frac{nNB(1 - p_b)B}{T} $$

(3)

In one-way relay transmission, each TDD subframe is further divided equally into two time slots which are used for uplink/downlink transmissions and relay transmissions. We assume there are still $n$ blocks are transmitted within a subframe, but the block size will vary due the change of subframe length. Therefore, the network throughput in one-way relay transmission, $S_o$, is calculated as

$$ S_o = \frac{nNB(1 - p_B)}{2T} $$

(4)

where $p_B$ is the error rate of block transmission with selection. $p_B$ is calculated as follows

$$ p_B = (1 - (1 - p_b)^\frac{B}{2})(1 - (1 - p_r)^\frac{B}{2}), $$

(5)
where \( p_r \) is the bit error rate of the relay transmission.

By substituting the above equation into Eq. (4), we get the throughput of the TDD network with one-way relay

\[
S_o = \frac{nNB(1 - (1 - (1 - p_b)^{\frac{N}{2}})(1 - (1 - p_r)^{\frac{N}{2}}))}{2T},
\]

(6)

In two-way network coding based relay transmission, we assume that the number of uplink-downlink pairs is \( m \). To maintain the same uplink-downlink traffic ratio as in direct transmissions, the subframe length is calculated by

\[
l = \frac{T}{3m + 2(N - 2m)}
\]

(7)

\[
= \frac{T}{2N - m},
\]

and the block size is calculated by

\[
L = \frac{NB}{2N - m},
\]

(8)

Therefore, we get the network throughput for two-way network coding based relay transmissions, \( S_t \), as shown in

\[
S_t = \frac{nNB(1 - (1 - (1 - p_b)^{\frac{N}{2}})(1 - (1 - p_r)^{\frac{N}{2}}))}{(2N - m)T},
\]

(9)

B. Outage Probability

We assume that a symbol \( s \) is transmitted in time slot \( n \) and a relay resends this symbol in time slot \( n + 1 \). Hence, the received signal at the receiver side is expressed as

\[
y_1(n) = \sqrt{P_1} h_1(n)s + z_1(n),
\]

(10)

and

\[
y_2(n + 1) = \sqrt{P_2} h_2(n + 1)s + z_2(n + 1),
\]

(11)

where \( P_1 \) and \( P_2 \) are transmit power of the base station and relay respectively, \( h_1(n) \) is the base station-user channel in time slot \( n \) and \( h_2(n + 1) \) is the relay-user channel in time slot \( n + 1 \), \( z_1(n) \) and \( z_2(n + 1) \) are the additive white Gaussian noise (AWGN) at the receiver side with zero mean and variance \( N_0 \).

Therefore, the mutual information from base station to network user in direct link, \( I_{1d} \), is

\[
I_{1d} = \log_2(1 + |h_1(n)|^2 r_1),
\]

(12)
where $r_1$ is transmit signal-to-noise (SNR) ratio of direct link. In a TDD network with one-way relay, the mutual information of direct link and relay link, $I_{1o}$ and $I_{2o}$, are

$$I_{1o} = \frac{1}{2} \log_2(1 + |h_1(n)|^2 r_1),$$  \hspace{1cm} (13)$$

and

$$I_{2o} = \frac{1}{2} \log_2(1 + |h_2(n + 1)|^2 r_2).$$ \hspace{1cm} (14)$$

where $r_2$ is transmit signal-to-noise (SNR) ratio of relay link. In the above two equations, the factor $\frac{1}{2}$ is added due to the fact that two time slots are used for transmitting one symbol in one way relay transmission. Similarly, we get the mutual information of direct link and relay link, $I_{1t}$ and $I_{2t}$, in a TDD network with network coding embedded two-way relay,

$$I_{1t} = \frac{2}{3} \log_2(1 + |h_1(n)|^2 r_1),$$ \hspace{1cm} (15)$$

and

$$I_{2t} = \frac{2}{3} \log_2(1 + |h_2(n + 1)|^2 r_2),$$ \hspace{1cm} (16)$$

An outage event occurs when the uplink/downlink transmission data rate, $R$, exceeds the channel capacity [22]-[23]. Since the base station-user channel and network-user channel are independent, we get the outage probability of TDD network with direct transmission only, one-way relay transmission and two-way relay transmission, $Pr_d$, $Pr_o$ and $Pr_t$,

$$Pr_d = Pr(I_{1d} < R) = Pr(|h_1(n)|^2 < \frac{2R - 1}{\lambda_1 r_1})$$ \hspace{1cm} (17)$$

$$Pr_o = Pr(I_{1o} < R)Pr(I_{2o} < R) = Pr(|h_1(n)|^2 < \frac{2R - 1}{r_1})Pr(|h_2(n + 1)|^2 < \frac{2R - 1}{r_2})$$ \hspace{1cm} (18)$$

$$Pr_t = Pr(I_{1o} < R)Pr(I_{2o} < R) = Pr(|h_1(n)|^2 < \frac{2^2 R - 1}{r_1})Pr(|h_2(n + 1)|^2 < \frac{2^2 R - 1}{r_2})$$ \hspace{1cm} (19)$$

Considering Rayleigh fading for both direct transmission channel and rely transmission channel, $|h_1(n)|^2$ and $|h_1(n)|^2$ follow exponential distribution as shown in

$$p(|h_1(n)|^2) = \frac{1}{\lambda_1} e^{-\frac{|h_1(n)|^2}{\lambda_1}},$$ \hspace{1cm} (20)$$
and
\[ p(|h_2(n+1)|^2) = \frac{1}{\lambda_2} e^{-\frac{|h_2(n+1)|^2}{\lambda_2^2}}, \]  
where \( \lambda_1 \) and \( \lambda_2 \) are the channel gain from base station to network user and the channel gain from relay to network user respectively. Hence, the closed-form outage probabilities \( P_{rd}, P_{ro} \) and \( P_{rt} \) are

\[ P_{rd} = 1 - e^{\frac{2R - 1}{\lambda_{1r1}}} \]

\[ P_{ro} = (1 - e^{\frac{2R - 1}{\lambda_{1r1}}})(1 - e^{\frac{2^{\frac{2R - 1}{2}}}{\lambda_{2r2}}}) \]

\[ P_{rt} = (1 - e^{\frac{2^{\frac{3}{2}}R - 1}{\lambda_{1r1}}})(1 - e^{\frac{2^{\frac{3}{2}}R - 1}{\lambda_{2r2}}}) \]

V. Numerical Results

In this section, we present the numerical results in order to illustrate the performance improvement of the proposed adaptive TDD networks. The first subsection shows the theoretical network throughput and outage probabilities of three types of TDD networks, i.e., a TDD network with direct link only, a TDD network with one-way relay and, an adaptive TDD network with network coding based two-way relay, respectively. In the second subsection, an application of this TDD network in vehicular applications is considered. Then the corresponding network throughput and outage probabilities of the TDD networks are presented.

A. Performance of TDD network

Fig. 7 presents the network throughput and outage probability performance of the network model as shown in Fig. 1. Following the LTE superframe configuration type 2, each superframe contains \( N = 10 \) subframes in the figures and the subframes are configured as \( UDUDUDUDUD \), where \( U \) stands for an uplink transmission subframe and \( D \) stands for a downlink transmission subframe, based on the uplink-downlink traffic requirement in our simulations. Each superframe equals to \( T = 10 \) ms and therefore each subframe is 1 ms. We also consider that each subframe contains \( n = 5 \) blocks and the block size is \( B = 5000 \) bits. The base station-user channel and relay-user channel are independent Rayleigh fading channels with the same channel gain \(-2 dB\). We also assume that the BPSK modulation is used in all network nodes (base station, users, relays).

The figure 6(a) and 6(b) show the network throughput performance considering a TDD network with direct link only, a TDD network with one-way relay, and an adaptive TDD network with network coding based two-way relay according to the Eqs. (3), (6), and (9). In figure 6(a), the dotted line illustrates the
network throughput performance of a TDD network without relays. We observe from this figure that this network achieves a maximum throughput 20 Mbps when the SNR is greater than 12dB at the transmitter side. However, the network throughput decreases when the SNR is less than 12dB and becomes 0 when the SNR is less than 8dB. This is mainly because the block error rate increases when the SNR is low and therefore it decreases the network throughput. The 3D plot in figure 6(a) illustrates the network throughput for a TDD network with one-way relay. We observe that the maximum throughput is 10 Mbps, which is half of the direct transmission case because that each subframe is divided into two slots in this type of network, no matter what the SNR at transmitter side. However, compared with the direct transmission case, the network can still achieve up to 10 Mbps throughput when the SNR is higher than 8dB at the relay transmitter side. Figure 6(b) shows the throughput of the proposed adaptive TDD network. In the figure, the network achieves the same throughput performance as direct transmission case when the direct link SNR is high enough. In addition, this network achieves 13.3 Mbps throughput when the relay transmission is involved, which is a 33% throughput improvement due to the advantage of network coding technique comparing with the one-way relay transmission. To summarize, the proposed adaptive TDD network has the same throughput performance as the direct transmission mode when the direct link SNR is high enough and outperform the one-way relay network when the SNR is low.

The figure 6(c) and (d) show the outage probability performance of these three types of TDD networks. In figure 6(d), the dotted line shows the outage probability of a TDD network with direct transmission only. The 3D plot in figure 6(c) shows the outage probability of a TDD network with one-way relay transmission and figure 6(d) shows the proposed adaptive TDD network with network coding based two-way relay transmission. In the figures, we observe that the outage probability performance of the proposed adaptive TDD network performs the same as the direct transmission case (dotted line) when the SNR is high enough at the transmitter side. However, the plot has a drop due to the diversity combine issue when the two-way relay is adaptively utilized when the SNR decreases. Meanwhile, we observe that this proposed adaptive TDD network always has a lower outage probability than the TDD network with one-way relay. To summarize, the proposed adaptive TDD network has the same outage performance as the direct transmission mode when the SNR is high and outperforms both the TDD networks with direct link only and the TDD network with one-way relay when the SNR is low.

B. Performance of a TDD vehicular network

In the foreseeable future, TDD network will also be used in vehicular communications to enable vehicles/passenger users to communicate either with roadside base stations via vehicle-to-infrastructure (V2I)
communication, or among different vehicles/passenger users via vehicle-to-vehicle (V2V) communication, which contributes to a safer and improved driving experience. In this subsection, we examine our proposed adaptive TDD network considering a V2I vehicular network as shown in Fig. 8. In the model, a roadside base station is located in the center of a cell while network users are randomly located along the road, which may be either within the cover range or beyond the cover range of the base station. Three scenarios of network users are illustrated. The first scenario, vehicle B and C, represents network users which are located with good cell coverage and thus has a reliable direct communication link with the base station. In this scenario, the base station and vehicle communicate under a satisfiable packet error rate. In the second scenario, User D, represents network users which are located at the cell edge and a cooperative relay is recommended in the communication pair to assist their communications. In the third scenario, the User A is located beyond the cover range of the base station and it does not have a direct communication link with the base station. In this case, a two-hop relay is needed to help the base station/network user to relay its communication packets. In the second and third scenarios, relays are involved in the communications and the relays can be either ordinary vehicle/passanger users or roadside deployed relay stations.

Fig. 9 and Fig. 10 illustrate the throughput and outage performance respectively. In the figures, we...
use the same superframe configuration parameters (LTE superframe configuration Type 2) as the previous subsection. Moreover, we assume that the roadside base station has a maximum coverage range 10 Km when it is operating with the maximum transmission power. To examine the coverage range of the roadside base station, we set the base station to operate with its maximum transmission power and the path loss, $PL$, is used to determine the received power at the receiver side, which is determined by the following equation

$$ PL = C + 20\log_{10}d + 20\log_{10}f \quad (25) $$

where $C$ is a constant, $d$ is the distance between the roadside base station and a vehicle user in meters, and $f$ is the operating frequency in MHz. In the figures, we also assume that the distance between a relay and a roadside base station is 6 Km. In Fig. 9, we observe that the TDD network without relay can achieve 20 Mbps throughput when the distance between the roadside base station and a vehicle user is less than $6.5\text{Km}$ and decreases when the distance increases. When the distance is larger than 10 Km, the throughput becomes 0 due to the low received SNR. When the one-way relay is used in a TDD network, we observe that the coverage distance increases to 13 Km while the maximum throughput is halved. By using network coding based two-way relay, a 33% higher maximum throughput is achieved compared with the one-way relay and meanwhile maintains the same coverage distance. In the proposed adaptive TDD network, it is seen from the figure that the same throughput as the direct transmission is achieved when the distance is less than 8 Km. However, when the distance is increasing, a 13.3 Mbps throughput is achieved without reducing the coverage range of the TDD network.

In Fig. 10, the outage performance proposed in the proposed adaptive TDD network always outperforms the direct transmission when the distance is larger than 8 Km due to the diversity combining techniques. However, the outage performance is the same as in the direct transmission case but worse than one-way and two-way relay transmission cases when the distance is small.
VI. CONCLUSION

In this paper, an adaptive TDD network with network coding based two-way relay is proposed. In this adaptive TDD network, the MAC sublayer is enabled to adaptively configure the uplink-downlink subframe structure to support direct link transmissions, cooperative relay transmissions and two-hop relay transmissions based on the channel condition. Moreover, to facilitate the implementation of this adaptive TDD network in a distributed manner, a novel opportunistic decoding scheme for receivers and a relay operation scheme are proposed in this paper. Based on the numerical results, we observe that this adaptive TDD network achieves the maximum network throughput and meanwhile extends the cell coverage range.
REFERENCES


