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Asynchronous Cooperative Protocols for Inter-vehicle Communications

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1. Introduction

Inter-vehicle communication is envisioned to play a very important role in the future, improving road safety and capacity. This can be achieved by utilizing cooperative relaying techniques where the communicating nodes exploit spatial diversity by cooperating with each other (Laneman et al., 2004). This alleviates the detrimental effects of fading and offers reliable data transfer. The source node broadcasts the signal to the destination node directly, and also through the relay nodes. Both the direct and relayed signals are combined at the destination. However, conventional cooperative communication systems require frame or symbol level synchronization between the cooperating nodes. The lack of synchronization results in inter-symbol interference (ISI) and degrades the system performance. This problem will be more severe in inter-vehicle communication as maintaining synchronization in fast moving nodes is very difficult. In this chapter, we present the major asynchronous cooperative communication protocols that can be employed for inter-vehicle communications. These are the asynchronous delay diversity technique (Wei et al., 2006), asynchronous space-time block code (STBC) cooperative system (Wang & Fu, 2007), and asynchronous polarized cooperative (APC) system (Sohaib & So, 2009; 2010).

2. Conventional cooperative communication system model

A three node cooperative network containing the source (S), relay (R) and destination (D) nodes is shown in the Fig. 1. The information will be transmitted from the source node to the destination node directly and also through the relay node. Both the direct and relay signals are combined at the destination using combiners (Brennan, Feb 2003). In general, there are two kinds of relaying modes; *amplify-and-forward (ANF)*, where the relay simply amplifies the noisy version of the signal transmitted by source, and *decode-and-forward (DNF)*, where relay decodes, re-encodes and re-transmits the signal.
The conventional ANF channel model is characterized by transmitting and receiving in orthogonal frequency bands or time slots (Laneman et al., 2004; Sohaib et al., 2009). Here we consider the ANF scheme with the relay node transmitting at the same frequency band as the source node, but in subsequent time-slot.

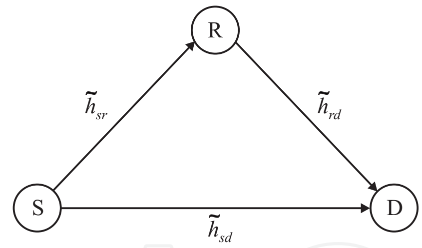

Fig. 1. Cooperative communication netwrok.

The channel $\tilde{h}_{ij}$ between the i-th transmit and j-th receive antenna is given by

$$\tilde{h}_{ij} = \frac{\sum_{u=0}^{U-1} h_{ij}(u)}{\sqrt{PL_{ij}}} \tag{1}$$

where, $h_{ij}(u)$ is the normalized channel gain, which is an independent and identically distributed (i.i.d.) complex Weibull random variable with zero mean. This describes the random fading effect of multipath channels, and is assumed to be frequenct selective fading with U the total number of frequency selective channel taps. Weibull distribution is used for the analysis of APC in vehicle-to-vehicle communication as it fits best (Matolak et al., 2006). The path loss factor PL_{ij} models the signal attenuation over distance, and is given by (Haykin & Moher, 2004)

$$PL_{ij} = \frac{(4\pi)^2}{G_t G_r \lambda^2}\left(d_{ij}\right)^{\alpha} = PL_0\left(d_{ij}\right)^{\alpha} \tag{2}$$

where PL_0 is the reference path loss factor, d_{ij} is the distance between i-th transmitter and j-th receiver, α is the path loss exponent depending on the propagation environment which is assumed to be the same over all links, λ is the wavelength, and G_t and G_r are the transmitter and receiver antenna gains respectively.

In a typical three node system, single transmission is normally divided into two timeslots (Peters & Heath, 2008; Tang & Hua, 2007). In the first timeslot, the source node broadcasts the signal to the destination and the relay node. The received signal at the destination node directly from the source node is

$$y_{sd}(t) = \sqrt{\frac{E^s}{PL_{sd}}} \sum_{u=0}^{U-1} h_{sd}(u)x(t-u) + n_d(t) \tag{3}$$

where x is the transmitted signal from the source with unit energy, E^s is the transmitted signal energy from the source, h_{sd} is the normalized channel gain from the source to the destination with a corresponding path loss of PL_{sd}, and $n_d(t)$ captures the effect of AWGN at the destination. Similarly, at the same timeslot the relay node receives the same signal from the source, given by

$$y_{sr}(t) = \sqrt{\frac{E^s}{PL_{sr}}} \sum_{u=0}^{U-1} h_{sr}(u)x(t-u) + n_r(t) \tag{4}$$

where h_{sr} is the normalized channel gain from the source to the relay with a corresponding path loss of PL_{sr}, and $n_r(t)$ is the AWGN at the relay.

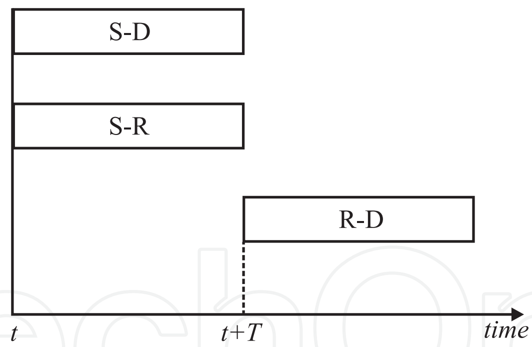

Fig. 2. Timing diagram of ANF cooperative scheme.

In the second timeslot the signal received at the relay node is amplified by a factor k'_r and forwarded to the destination given by

$$y_{rd}(t+T) = \frac{k'_r}{\sqrt{PL_{rd}}} \sum_{u=0}^{U-1} h_{rd}(u) y_{sr}(t-u) + n_d(t+T) \tag{5}$$

where $T = LT_s$ is the timeslot or frame duration with L being the total number of symbols per frame and T_s the symbol period, h_{rd} is the normalized channel gain from the relay to destination node having a corresponding path loss of PL_{rd}, and $n_d(t+T)$ is the AWGN at the destination node. The transmitter estimates path loss through the reverse link and is assumed to be perfectly estimated. On the other hand, instantaneous channel fading gain is not assumed to be known at the transmitter, as it requires feedback information. Therefore, setting identical received signal energy from the direct and relayed link, the amplification factor k'_r is given by

$$k'_r = \sqrt{\frac{E^s \, \mathbb{E}\left[\left|\tilde{h}_{sd}\right|^2\right]}{E^r \, \mathbb{E}\left[\left|\tilde{h}_{rd}\right|^2\right]}} = \sqrt{\frac{E^s/PL_{sd}}{\left(E^s/PL_{sr} + N_0\right)/PL_{rd}}} \tag{6}$$

where E^r is the received signal energy at the relay node. All AWGN noises are modeled as zero mean mutually independent circular symmetric complex Gaussian random sequences with power spectral density (PSD) N_0. Exact channel state information (CSI) is assumed to be available at the receiver only, and not at the transmitter.

For conventional ANF system, the signal in (3) and (5) are combined at the destination node using diversity combiners, e.g. Maximal Ratio Combiner (MRC). The diversity gain achieved through cooperation can compensate the additional noise in the relay (Laneman et al., 2004). Hence, cooperative diversity schemes achieve better performance than non-cooperative schemes.

Fig. 2 illustrates the timing diagram of ANF cooperative system, where, t is the time when the source node starts transmitting the data to the destination and relay nodes. The relay node will start transmitting after a duration of T. Therefore it takes two orthogonal channels for one complete transmission, thus decreases the spectral efficiency of the system. Also frame level synchronization is required in conventional ANF, which is not always achievable in wireless communication. The diversity gain achieved through cooperation can compensate for the additional noise in the relay (Laneman et al., 2004). Hence, the cooperative diversity schemes achieve better performance than non-cooperative schemes.

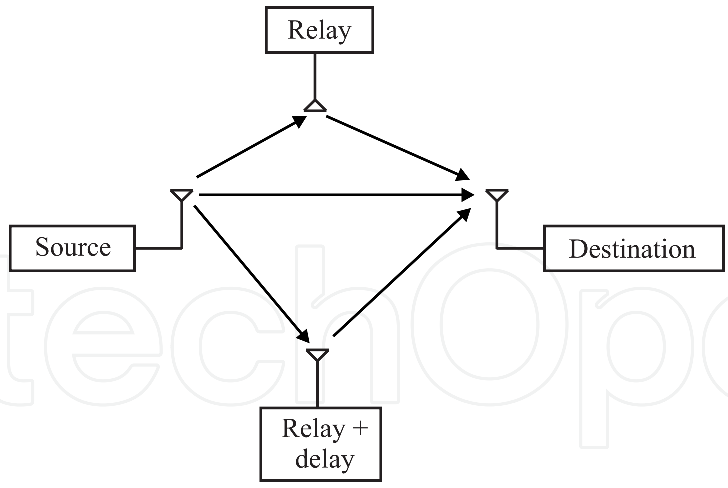

Fig. 3. System structure of cooperative communications.

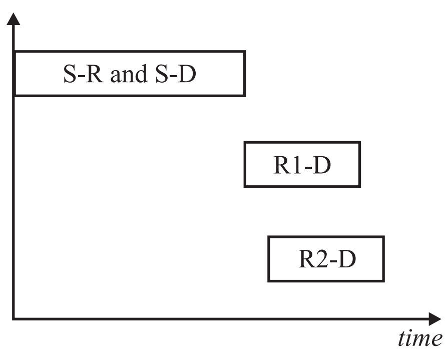

Fig. 4. Timing diagram of asynchronous delay diversity cooperative scheme.

3. Asynchronous cooperative systems

In this section we present a brief summary of the three major inter-vehicle asynchronous cooperative communication systems.

3.1 Asynchronous delay diversity technique

In (Wei et al., 2006), a distributed delay diversity approach is proposed in the Relay-Destination (R-D) link to achieve spatial diversity as shown in Fig. 3. Error detection schemes such as cyclic redundancy check (CRC) is employed at the relay nodes to determine whether the received packet is error free or not. If the received packet is error-free, the relay node will then forward the information packet to the destination, after an additional artificial delay. On the contrary if the packed is in error, it will be dropped at the relay node. Assuming the CRC code can perfectly detect any packet error the forwarded signal from the relay is thus a delayed version of the transmitted symbols. Hence, the destination node will see an equivalent frequency selective fading channel in the form of artificially introduced delays. Fig. 4 illustrates the timing diagram of this scheme.

To equalize the frequency selectivity, a decision feedback equalizer (DFE) is employed at the destination node. It also combines the inputs from the direct link channel, and relay link ones. Although this scheme can mitigate the synchronization problem, it uses half duplex relay node which reduces the spectral efficiency due to the bandwidth expansion or extended time duration. Constellation size has to be increased to maintain the spectral efficiency which then reduces the performance gain over non-cooperative single-input single-output (SISO) scheme.

3.2 Asynchronous space-time block code cooperative system

Instead of using the simple delay diversity code in the R-D link, the asynchronous STBC is proposed in (Wang & Fu, 2007) to achieve distributed cooperative diversity. The system and timing diagram for this scheme is identical to that of the asynchronous delay diversity scheme in Fig. 3 and Fig. 4. At the relay, the detected symbols are mapped into the orthogonal STBC matrix. Each relay then randomly select one row from this matrix for transmission. The random cyclic delay diversity technique is then applied to make the equivalent channels frequency selective. At the destination node the frequency domain equalizer (FDE) is employed to combine and equalize the received signal.

The scheme has a disadvantage that it could suffer performance degradation due to diversity loss by random row selection. Similar to the previous scheme, this system also assumes the relay to be half duplex which results in low spectral efficiency.

3.3 Asynchronous polarized cooperative system

Most cooperative communication systems, including (Wang & Fu, 2007; Wei et al., 2006), employ half duplex relays. This is because full duplex relay that uses the same time and frequency for transmission and reception is difficult to implement. The transmitted signal will overwhelm the received signal. In view of this, the asynchronous polarized cooperative (APC) system is proposed in (Sohaib & So, 2009; 2010), and is illustrated in Fig. 5. It allows full duplex relay operation, and does not require frame of symbol level synchronization. In this scheme every vehicle is equipped with dual polarized antennas that can auto-configure itself to be the source, relay and destination node. The vehicle working as a source only activates the vertical polarized antenna for transmission, whereas the destination vehicle configures the dual polarized antennas for reception. The vehicle working as a relay uses dual polarized antennas for transmission and reception at the same time and at the same frequency thereby achieving the full duplex ANF communication and effectively reducing the transmission duration and increasing the throughput rate. The solid lines represent transmission and reception on the same polarization, also known as co-polarization. On the other hand, the dotted lines represent transmission in one polarization but reception in the other polarization, also known as cross-polarization. The effect of cross-polarization is considered as it is impossible to maintain the same polarization between the transmitter and the receiver due to the complex propagation environment in terrestrial wireless communications. For more practical consideration, path loss is also included in the analysis.

For a relay to operate in full duplex mode the transmission and reception channels must be orthogonal either in time-domain or in frequency domain, otherwise the transmitted signal will interfere with the received signal. In theory, it is possible for relay to cancel out interferences as it has the knowledge of transmitted signal. In practice, however, the transmitted signal is 100-150dB stronger than the received signal and any error in the interference cancellation can potentially be disastrous (Fitzek & Katz, 2006). Due to this reason, the installation of co-polarized antennas at the relay node in place of dual-polarized antennas is not feasible for full duplex relay. However, with dual-polarized antenna the transmitted signal on one polarization is orthogonal to the received signal at another polarization, thereby, enabling the relay to communicate in full duplex mode, not the overall system.

The source node will broadcast using vertical polarization. The vertically polarized received signal at the relay node is the same as (4).

The received signal at the relay node is amplified by a factor k_r, and transmitted immediately to the destination node through horizontal polarization. Radio propagation and signal

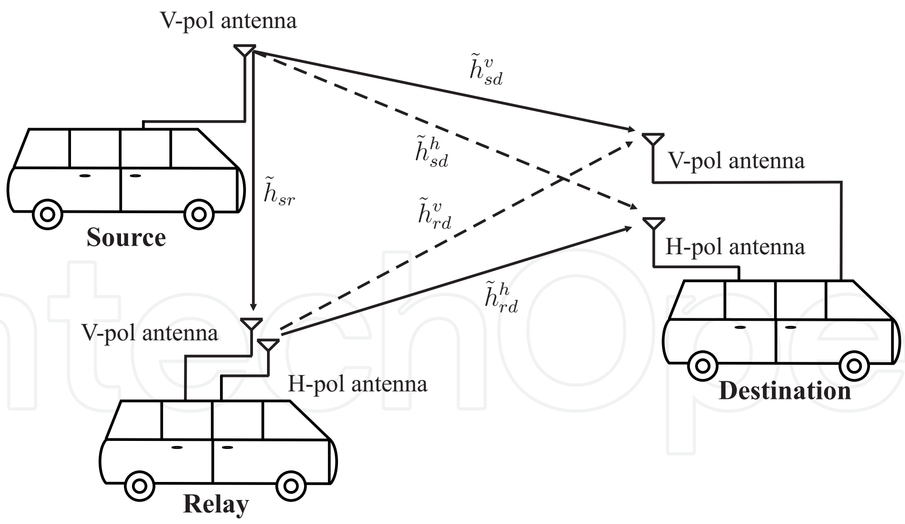

Fig. 5. Asynchronous polarized cooperative system for inter-vehicular communication.

processing at the relay node will cause some additional time delay τ, which could be a few symbols duration and is much shorter than the frame duration T. It must be noted that the APC system does not require symbol level synchronization, between the source and relay, and thus τ can be any positive real number. Fig. 6 illustrates the timing diagram of this scheme. The vertically and horizontally polarized signal received at the destination, denoted as y_{d_v} and y_{d_h} respectively, are given by

$$y_{d_v}(t) = \sqrt{E^s}\, \tilde{h}^v_{sd}\, x(t-u) + k_r\, \tilde{h}^v_{rd}\, y_{sr}\,(t-\tau-u) + n_{d_v}(t) \tag{7}$$

and

$$y_{d_h}(t) = \sqrt{E^s}\, \tilde{h}^h_{sd}\, x(t-u) + k_r\, \tilde{h}^h_{rd}\, y_{sr}\,(t-\tau-u) + n_{d_h}(t). \tag{8}$$

The received signals of the above equations can therefore be written in matrix form as

$$\underbrace{\begin{bmatrix} y_{d_v}(t) \\ y_{d_h}(t) \end{bmatrix}}_{\mathbf{y}_d} = \underbrace{\begin{bmatrix} \tilde{h}^v_{sd} & \tilde{h}^v_{rd} \\ \tilde{h}^h_{sd} & \tilde{h}^h_{rd} \end{bmatrix}}_{\mathbf{H}} \begin{bmatrix} \sqrt{E^s}x(t-u) \\ k_r y_{sr}(t-\tau-u) \end{bmatrix} + \underbrace{\begin{bmatrix} n_{d_v}(t) \\ n_{d_h}(t) \end{bmatrix}}_{\mathbf{n}} \tag{9}$$

where $\mathbf{n}$ is the 2×1 i.i.d. zero mean complex AWGN vector with variance $\mathbb{E}\left[\mathbf{n}\,\mathbf{n}^H\right] = N_0\,\mathbf{I}$, and $\mathbf{I}$ is an identity matrix. The diagonal elements of $\mathbf{H}$ correspond to co-polarization, while the off-diagonal elements correspond to cross-polarization. The relay amplification factor k_r is

$$k_r = \sqrt{\frac{E^s\left(\mathbb{E}\left[\left|\tilde{h}^v_{sd}\right|^2\right] + \mathbb{E}\left[\left|\tilde{h}^h_{sd}\right|^2\right]\right)}{E^r\left(\mathbb{E}\left[\left|\tilde{h}^v_{rd}\right|^2\right] + \mathbb{E}\left[\left|\tilde{h}^h_{rd}\right|^2\right]\right)}} \tag{10}$$

where E^r is the received signal energy at the relay node given by

$$E^r = E^s\,\mathbb{E}\left[\left|\tilde{h}_{sr}\right|^2\right] + N_0. \tag{11}$$

Since the source and relay node are spatially separated apart, we can assume the channel from the source to the destination is not correlated with the channel from the relay to the

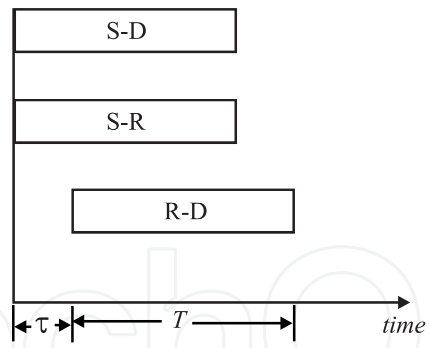

Fig. 6. Timing diagram of APC scheme.

destination. In other words, the co-polarization elements of the channel h^v_{sd} and h^h_{rd} and the cross-polarization elements h^h_{sd} and h^v_{rd} are assumed to be completely un-correlated. Therefore

$$\mathbb{E}\left[h^v_{sd}h^{h*}_{rd}\right] = \mathbb{E}\left[h^h_{sd}h^{v*}_{rd}\right] = 0 \tag{12}$$

and

$$\mathbb{E}\left[h^v_{sd}h^{v*}_{rd}\right] = \mathbb{E}\left[h^h_{sd}h^{h*}_{rd}\right] = 0. \tag{13}$$

We define the receive correlation coefficient as

$$\rho_r = \frac{\mathbb{E}\left[h^v_{sd}h^{h*}_{sd}\right]}{\sqrt{\chi}} = \frac{\mathbb{E}\left[h^v_{rd}h^{h*}_{rd}\right]}{\sqrt{\chi}}. \tag{14}$$

At the destination node, the vertical and horizontal polarized signals are received at different time due to the signal processing and additional propagation delay τ caused by the relay. Because of cross polarization, the delayed signal from the relay becomes an ISI. Therefore equalization for each polarization is required. As there are two branches from the vertical and horizontal polarization, diversity combiner is needed. The frequency domain diversity combiner and equalizer (FDE-MRC) is therefore used and is shown in Fig. 7. Assuming that

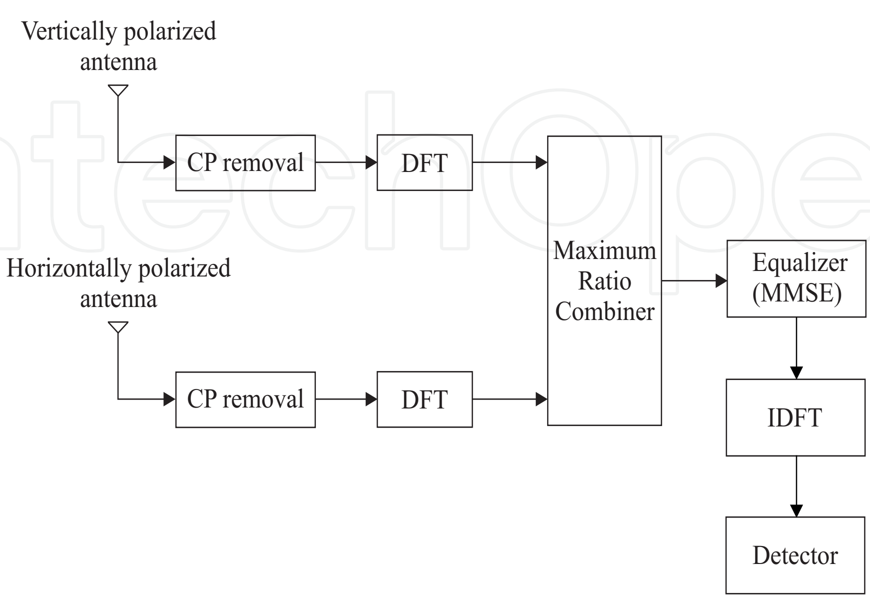

Fig. 7. Receiver structure of the APC MIMO system.

cyclic prefix (CP) with duration longer than delay τ is inserted before transmission from the source node, and removed at the destination node, the signals received at the destination node from the source and relay nodes are transformed into frequency domain by taking L points discrete Fourier transform (DFT). The resulting signal spectras at the k-th subcarrier from vertical and horizontal polarized branches are respectively given by

$$\begin{aligned} Y_{d_v}(k) &= \sqrt{E^s}\, X(k) \left[\tilde{h}^v_{sd} + k_r \tilde{h}^v_{rd} \tilde{h}_{sr} e^{-j2\pi \frac{k}{L}\tau}\right] + k_r \tilde{h}^v_{rd} N_r(k) e^{-j2\pi \frac{k}{L}\tau} + N_{d_v}(k) \\ &\triangleq \sqrt{E^s} X(k)\, H_v(k) + N_v(k) \end{aligned} \tag{15}$$

and

$$\begin{aligned} Y_{d_h}(k) &= \sqrt{E^s}\, X(k) \left[\tilde{h}^h_{sd} + k_r \tilde{h}^h_{rd} \tilde{h}_{sr} e^{-j2\pi \frac{k}{L}\tau}\right] + k_r \tilde{h}^h_{rd} N_r(k) e^{-j2\pi \frac{k}{L}\tau} + N_{d_h}(k) \\ &\triangleq \sqrt{E^s} X(k)\, H_h(k) + N_h(k) \end{aligned} \tag{16}$$

where $k = \{1, 2, \ldots, L\}$, $X(k)$ is the transmitted signal in frequency domain, $N_r(k)$ is the relay noise in frequency domain, and $N_v(k)$ and $N_h(k)$ are the effective noises at the vertical and horizontal antennas respectively at the destination node, $H_v(k)$ and $H_h(k)$ are the effective channels at vertical and horizontal antennas respectively at the destination node given by

$$H_v(k) = \tilde{h}^v_{sd} + k_r \tilde{h}^v_{rd} \tilde{h}_{sr} e^{-j2\pi \frac{k}{L}\tau} \tag{17}$$

and

$$H_h(k) = \tilde{h}^h_{sd} + k_r \tilde{h}^h_{rd} \tilde{h}_{sr} e^{-j2\pi \frac{k}{L}\tau}. \tag{18}$$

The polarized frequency domain signals $Y_{d_v}(k)$ and $Y_{d_h}(k)$ are combined through MRC at the destination node and the resultant signal spectrum $Y(k)$ is

$$Y(k) = Y_{d_v}(k) H^*_v(k) + Y_{d_h}(k) H^*_h(k). \tag{19}$$

The combined signal $Y(k)$ is input to MMSE equalizer given by

$$W(k) = \arg\min_{W}\, \mathbb{E}_h \left[\left| W(k)\, Y(k) - \sqrt{E^s} X(k) \right|^2\right] \tag{20}$$

where $\mathbb{E}_h[.]$ denotes the expectation conditioned on the channel gains. For ease of notation and without loss of generality, we drop the index k in the following derivation. Substituting the value of Y from (15), (16), and (19) into the objective function of (20)

$$\begin{aligned} J =& \mathbb{E}_h \left[\left| W \left(\sqrt{E^s} X |H_v|^2 + N_v H^*_v + \sqrt{E^s} X |H_h|^2 + N_h H^*_h\right) - \sqrt{E^s} X \right|^2\right] \\ =& \mathbb{E}_h \left[\left| \left(W |H_v|^2 + W |H_h|^2 - 1\right) \sqrt{E^s} X + W N_v H^*_v + W N_h H^*_h \right|^2\right]. \end{aligned} \tag{21}$$

Solving the above equation for minimum value of W, we take the derivate of J w.r.t. W and set it to 0, i.e. $\frac{dJ}{dW} = 0$

$$\begin{aligned}\Rightarrow & E^s \left(|H_v|^4 W^* + |H_h|^4 W^* + 2\,|H_v H_h|^2 W^* - |H_v|^2 - |H_h|^2 \right) \\ & + N_0^v |H_v|^2 W^* + N_0^h |H_h|^2 W^* = 0\end{aligned}$$

$$\begin{aligned}\Rightarrow & \left(E^s |H_v|^4 + E^s |H_h|^4 + 2\,|H_v H_h|^2 + |H_v|^2 N_0^v + |H_h|^2 N_0^h \right) W^* \\ & = E^s \left(|H_v|^2 + |H_h|^2 \right)\end{aligned} \quad (22)$$

Rearranging (22) we obtain,

$$W^* = \frac{E^s \left(|H_v|^2 + |H_h|^2 \right)}{E^s \left(|H_v|^4 + |H_h|^4 + 2\,|H_v H_h|^2 \right) + |H_v|^2 N_0^v + |H_h|^2 N_0^h} \quad (23)$$

Assuming $H = |H_v|^2 + |H_h|^2$, (23) becomes,

$$W^* = \frac{H}{|H|^2 + |H_v|^2 \frac{N_0^v}{E^s} + |H_h|^2 \frac{N_0^h}{E^s}}. \quad (24)$$

Taking the conjugate on both side and adding the index k, we obtain the final form

$$W(k) = \frac{H^*(k)}{|H(k)|^2 + |H_v(k)|^2 \frac{N_0^v}{E^s} + |H_h(k)|^2 \frac{N_0^h}{E^s}} \quad (25)$$

where

$$H(k) = |H_v(k)|^2 + |H_h(k)|^2, \quad (26)$$

$$\begin{aligned}N_0^v &= N_0 \left(1 + k_r^2\, \mathbb{E}\left[\left| \tilde{h}_{rd}^v \right|^2 \right] \right) \\ &= N_0 \left(1 + \frac{k_r^2\, \chi}{PL_{rd}^v} \right)\end{aligned} \quad (27)$$

and

$$\begin{aligned}N_0^h &= N_0 \left(1 + k_r^2\, \mathbb{E}\left[\left| \tilde{h}_{rd}^h \right|^2 \right] \right) \\ &= N_0 \left(1 + \frac{k_r^2}{PL_{rd}^h} \right).\end{aligned} \quad (28)$$

As the dual polarized antennas at the destination node are closely spaced, we can assume the distance for the cross-polarized channels from the same node are the same, i.e., $d_{sd}^v = d_{sd}^h = d_{sd}$ and $d_{rd}^v = d_{rd}^h = d_{rd}$. Therefore (27) and (28) becomes

$$N_0^v = N_0 \left(1 + \frac{k_r^2 \chi}{PL_{rd}} \right) \quad (29)$$

and

$$N_0^h = N_0 \left(1 + \frac{k_r^2}{PL_{rd}}\right). \tag{30}$$

The detected data in frequency domain is then transformed back to time domain by using inverse discrete Fourier transform (IDFT). Due to the full duplex nature of the relay, the transmission time is reduced, which in turn increases the data rate as compared to the conventional ANF protocol. Also no frame or symbol synchronization is required at the relay node because of the use of FDE-MRC at the destination node.

3.4 Capacity analysis of asynchronous polarized cooperative system

In this section, the capacity of the APC scheme with one relay node will be presented. For fairer comparison, we also present the capacity of ANF cooperative system which employs dual polarized antenna at the destination node, where polarization diversity is also exploited.

3.4.1 Asynchronous polarized cooperative scheme

Given the channel information at the receiver, the ergodic capacity of the system in (15) and (16) can be computed as

$$\begin{aligned} C &= \max_{p(x)} I(x;\mathbf{y}_d) = \frac{L}{L+\tau}\,\mathbb{E}\left[\log_2\left(1+\frac{E^s}{G}\left(\mathbb{E}_h\left[\frac{|H_v|^2}{|N_v|^2}+\frac{|H_h|^2}{|N_h|^2}\right]\right)\right)\right] \\ &\cong \mathbb{E}\left[\log_2\left(1+\frac{E^s}{GL}.\mathbb{E}_h\left[\sum_{k=1}^{L}\frac{\left|\tilde{h}_{sd}^v+\sqrt{k_r}\tilde{h}_{rd}^v\tilde{h}_{sr}e^{-j2\pi\frac{k}{L}\tau}\right|^2}{\left|\sqrt{k_r}\tilde{h}_{rd}^v N_r(k)e^{-j2\pi\frac{k}{L}\tau}+N_{d_v}(k)\right|^2} + \sum_{k=1}^{L}\frac{\left|\tilde{h}_{sd}^h+\sqrt{k_r}\tilde{h}_{rd}^h\tilde{h}_{sr}e^{-j2\pi\frac{k}{L}\tau}\right|^2}{\left|\sqrt{k_r}\tilde{h}_{rd}^h N_r(k)e^{-j2\pi\frac{k}{L}\tau}+N_{d_h}(k)\right|^2}\right]\right)\right] \\ &= \mathbb{E}\left[\log_2\left(1+\frac{E^s}{GLN_0}\left(\frac{\sum_{k=1}^{L}\left|\tilde{h}_{sd}^v+\sqrt{k_r}\tilde{h}_{rd}^v\tilde{h}_{sr}e^{-j2\pi\frac{k}{L}\tau}\right|^2}{1+k_r\left|\tilde{h}_{rd}^v\right|^2} + \frac{\sum_{k=1}^{L}\left|\tilde{h}_{sd}^h+\sqrt{k_r}\tilde{h}_{rd}^h\tilde{h}_{sr}e^{-j2\pi\frac{k}{L}\tau}\right|^2}{1+k_r\left|\tilde{h}_{rd}^h\right|^2}\right)\right)\right] \end{aligned} \tag{31}$$

where $\mathbb{E}_h[.]$ denotes the expectation conditioned on the channel gains, G is a normalization factor that is used to make sure that the transmission energy of the APC scheme is the same as that of non-cooperative scheme, and is given by

$$G = 1 + \frac{PL_{rd}}{PL_{sd}}. \tag{32}$$

Notice that the pre-log factor $\frac{L}{L+\tau}$ can be approximated to be one as the frame length L is much larger than the delay τ. Hence the APC scheme will have a higher capacity than the conventional scheme, which inevitably has the 1/2 pre-log factor.

3.4.2 Polarized ANF

As conventional ANF does not have the cross polarized channels, a polarized ANF system is presented in this subsection for fairer comparison with the APC scheme. The system model of polarized ANF with vertical polarized source antenna, vertical polarized relay antenna and dual polarized destination antennas is given as

$$\mathbf{y}_{pa} = \mathbf{H}_{pa} \sqrt{E^s}\, x(t-u) + \mathbf{n}_{pa}$$

where $\mathbf{H}_{pa} = \left[\tilde{h}^v_{sd} \;\; \tilde{h}^h_{sd} \;\; \sqrt{k_r}\tilde{h}^v_{rd}\tilde{h}_{sr} \;\; \sqrt{k_r}\tilde{h}^h_{rd}\tilde{h}_{sr}\right]^T$ and

$$\mathbf{n}_{pa} = \underbrace{\begin{bmatrix} 1\,0\,0\,0 & 0 \\ 0\,1\,0\,0 & 0 \\ 0\,0\,1\,0 & \sqrt{k_r}\,\tilde{h}^v_{rd} \\ 0\,0\,0\,1 & \sqrt{k_r}\,\tilde{h}^h_{rd} \end{bmatrix}}_{\mathbf{Q}} \begin{bmatrix} n_{d_v}(t) \\ n_{d_h}(t) \\ n_{d_v}(t+T) \\ n_{d_h}(t+T) \\ n_r(t) \end{bmatrix}$$

where $\tilde{h}^v_{sd}$ and $\tilde{h}^v_{rd}$ are the co-polarized channels and $\tilde{h}^h_{sd}$ and $\tilde{h}^h_{rd}$ are the cross-polarized channels. The ergodic capacity of the polarized ANF is thus given by

$$C_{pa} = \frac{1}{2}\mathbb{E}\left[\log_2 \det\left(\mathbf{I} + \frac{E^s}{GN_0}\mathbf{H}_{pa}\mathbf{H}^H_{pa}\left(\mathbf{Q}\mathbf{Q}^{\mathbf{H}}\right)^{-1}\right)\right] \tag{33}$$

where the normalization factor G is identical to (32). It can be noted that the 1/2 pre-log factor in (33) shows that polarized ANF also requires two timeslots for one complete transmission.

3.5 Energy analysis of asynchronous polarized cooperative system

Cooperative communication achieves diversity through spatially separated cooperating nodes. In most potential applications, these nodes are battery powered. Therefore energy consumption must be minimized without compromising the transmission quality. As more RF front ends are used by polarized antennas in the APC scheme, the total energy requirement to achieve a required quality must be compared to the conventional ANF. In this section we formulate the transmission energy consumption and total energy consumption of the APC scheme.

In the following analysis, the energy consumption model developed by Cui *et. al.* is used (Cui et al., 2004). The total energy consumption model that includes both the transmission energy and the circuit energy consumption per bit is given by

$$E_{bt} = \frac{(P_{PA} + P_C)}{B\, R_b} \tag{34}$$

where P_C is the power consumption of all circuit blocks, B is the bandwidth, R_b is the bit rate, and P_{PA} is the power consumption of all power amplifiers, which depends on the transmit power P_{out},

$$P_{out} = E_T\, R_b\, B \tag{35}$$

where E_T is the sum of transmission energy from both the source and relay nodes. For the APC scheme E_T can be written as

$$E_T = E^s + k_r\, E^r = E^s \left(1 + \frac{\mathbb{E}\left[\left|\tilde{h}^v_{sd}\right|^2\right] + \mathbb{E}\left[\left|\tilde{h}^h_{sd}\right|^2\right]}{\mathbb{E}\left[\left|\tilde{h}^v_{rd}\right|^2\right] + \mathbb{E}\left[\left|\tilde{h}^h_{rd}\right|^2\right]} \right)$$

$$= E^s \left(1 + \frac{1/PL_{sd} + \chi/PL_{sd}}{\chi/PL_{rd} + 1/PL_{rd}} \right) = E^s \left(1 + \frac{PL_{rd}}{PL_{sd}} \right). \quad (36)$$

The power consumption of the power amplifies can be approximated as

$$P_{PA} = (1+\psi)\, P_{out} \quad (37)$$

where $\psi = (\xi/\eta) - 1$, with η the drain efficiency of the RF power amplifier and ξ the peak to average ratio, which depends on the modulation scheme and the associated constellation size M Cui et al. (2004)

$$\xi = 3\frac{M - 2\sqrt{M} + 1}{M - 1}. \quad (38)$$

The power consumption of all circuit blocks along the signal path is given by

$$P_C \approx M_t\,(P_{DAC} + P_{MIX} + P_{FILT}) + 2P_{SYN} + M_r\,(P_{LNA} + P_{MIX} + P_{IFA} + P_{FILR} + P_{ADC}) \quad (39)$$

where P_{DAC}, P_{MIX}, P_{FILT}, P_{SYN}, P_{LNA}, P_{IFA}, P_{FILR}, P_{ADC} are the power consumption values of the digital-to-analog converter (DAC), the mixer, the active filter at transmitter side, the frequency synthesizer, the low-noise amplifier, the intermediate frequency amplifier, the active filter at receiver side, and the analog-to-digital converter (ADC) respectively. M_t and M_r is the number of RF chains involved in one complete transmission at transmitter and receiver side respectively. Although the APC scheme has two extra physical antennas installed as compared to conventional ANF, both schemes effectively use the same number of RF chains for one complete transmission. It is because conventional ANF takes two timeslots for one complete transmission, which uses the RF chains again at the relay and the destination. Simulation results for energy analysis are shown in the next section under the same throughput and BER requirement.

4. Simulation results of asynchronous polarized cooperative system

Computer based Monte-Carlo simulations are carried out to illustrate the BER performance, capacity and energy consumption of the APC system. In order to provide a fair comparison among different schemes, spectral efficiency is kept constant for all protocols and is set to be 2bps/Hz. The SISO and the APC scheme uses QPSK, whereas the ANF protocol uses 16QAM for one relay network. This is because the SISO and the APC scheme takes approximately one time-slot for complete transmission of one data frame, whereas conventional ANF protocol takes two time-slots. For both the polarized ANF and the APC scheme, the cross-polarized channel power (χ) and receiver correlation coefficient (ρ_r) are set to be 0.4 and 0.5 respectively. The time delay τ is assumed to be one symbol period. To obtain reasonable values of received SNR, the transmitted signal from the source node is amplified by $\sqrt{PL_{sd}}$ to compensate the path loss. The direct link SNR after this normalization is defined as γ_{sd}. For the ANF and APC scheme, normalization factor G in (32) is used to ensure the same total transmission power as the SISO. Hence the normalization SNR γ_{sd} can be used as a reference for all schemes in capacity, and BER analysis. Table 1 summarizes the system parameters for all simulations, which are mostly based on (Cui et al., 2004), and (Cui et al., 2003). The parameter f_c is the carrier frequency, $\bar{P}_b$ is the average probability of error for energy consumption analysis, and M_L is the link margin compensating the hardware process variations and other background interference and noise. The number of transmit antennas M_t and receive antennas M_r involved in one complete transmission are respectively 2 and 3 for conventional and polarized ANF as well as the APC schemes, whereas they are both one for SISO scheme. Table 2 shows the parameters for the tapped delay line channel model derived by Matolak *et. al* for vehicle to vehicle communication (Matolak et al., 2006).

P_{DAC} = 15.4mW	$G_t G_r$ = 5dBi
P_{MIX} = 30.3W	$\alpha = 3$
P_{FILT} = 2.5mW	f_c = 5.12GHz
P_{FILR} = 2.5mW	$\eta = 0.35$
P_{SYN} = 50mW	$\bar{P}_b = 10^{-4}$
P_{LNA} = 20mW	M_L = 40dB
P_{IFA} = 3mW	B = 10MHz
P_{ADC} = 6.7mW	

Table 1. System Parameters.

For capacity and BER analysis, the source to destination node distance d_{sd} is set to be $200m$. The relay node is set at the midpoint between the source and destination node, i.e, $d_{sr} = d_{rd} = 100m$. For energy analysis, various positions of the relay node are considered.

Tap Index	Fractional Tap Energy	Weibull Shape Factor (b)	Weibull Scale Factor (a)
1	0.7018	2.49	0.8676
2	0.1158	1.75	0.3291
3	0.0543	1.68	0.2226
4	0.0391	1.72	0.1903
5	0.0259	1.65	0.1528
6	0.0198	1.60	0.1322
7	0.0118	1.69	0.1040

Table 2. Vehicle to vehicle channel model (Matolak et al., 2006).

The increase in capacity of the APC scheme as compared to the conventional ANF scheme is demonstrated in Fig. 8. The capacity of the APC scheme significantly outperforms the conventional ANF protocols due to the relay's full duplex capability. For polarized ANF, the use of dual polarized antenna at the destination node provides a marginal increase in capacity. Therefore, even if polarized antennas are also used, the APC scheme has a significant capacity advantage over the polarized ANF scheme. The APC scheme without cross-polarization has slightly less capacity than the APC system with cross-polarization but still it is higher than the ANF systems.

The BER performance comparison among the SISO, ANF protocol, and the APC system is presented in Fig. 9. The APC system without cross-polarization has a gain of about 4.5dB over the conventional ANF protocol at BER 10^{-3}. Thus the cost of using dual polarized antennas and separate RF chains at the relay node is justified by the significantly lowered BER. With the presence of cross-polarization, the performance further improves because

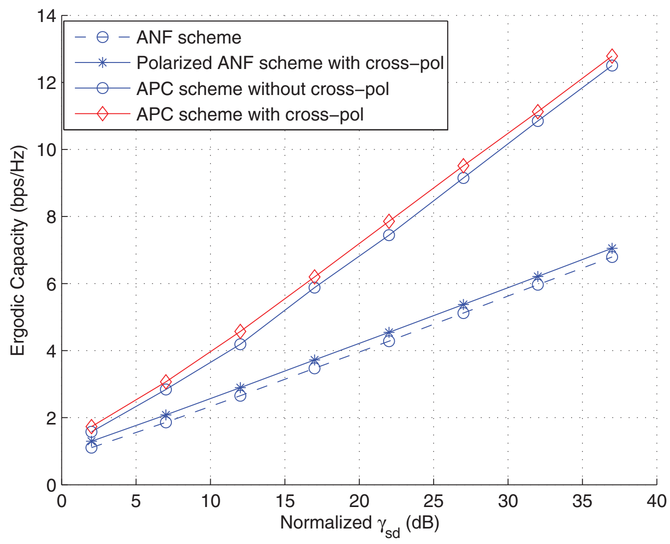

Fig. 8. Capacity comparison of one relay APC scheme.

polarization diversity can be achieved. The polarized ANF also has a marked improvement, but is approximately 3dB worse than the APC scheme. Another observation is the differences in the asymptotic slope of SISO to the APC scheme. It verifies that diversity is achieved for cooperative schemes with and without cross-polarization.

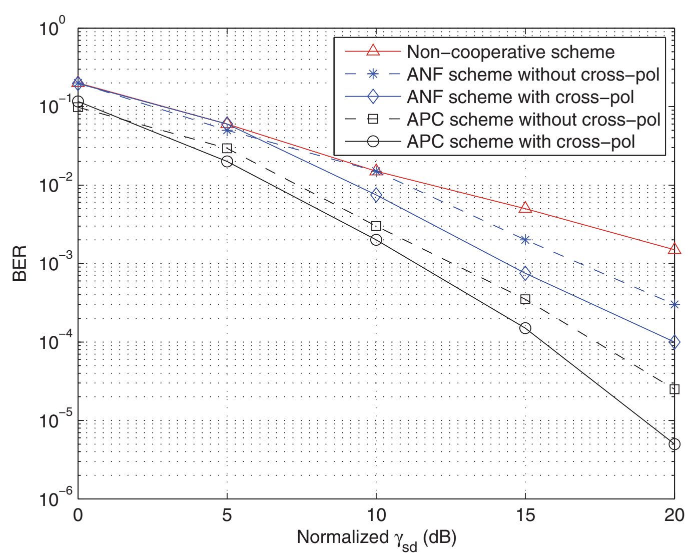

Fig. 9. BER performance of APC system.

As more RF front ends are installed in the APC scheme, the total energy required to achieve a particular quality is compared with the conventional ANF and SISO schemes in Fig. 10. The total energy consumption is calculated using (36), where E^s is obtained using direct link SNR γ_{sd} observed at BER=10^{-4}, where $\gamma_{sd} = E^s/N_0$. The direct link SNR is obtained by evaluating the BER over 10,000 randomly generated channel samples at each transmission distance. It can be observed that the APC scheme becomes more energy-efficient than both the ANF and SISO protocols when $d_{sd} \geq 23m$. The crossover point indicates the distance where the transmission energy saving exceeds the extra circuit energy consumption in the APC scheme comparing to the SISO and ANF scheme. In addition, for practical applications, the source to destination node speration will be mostly larger than 20m. Hence, the APC scheme will consume less energy in realistic scenario.

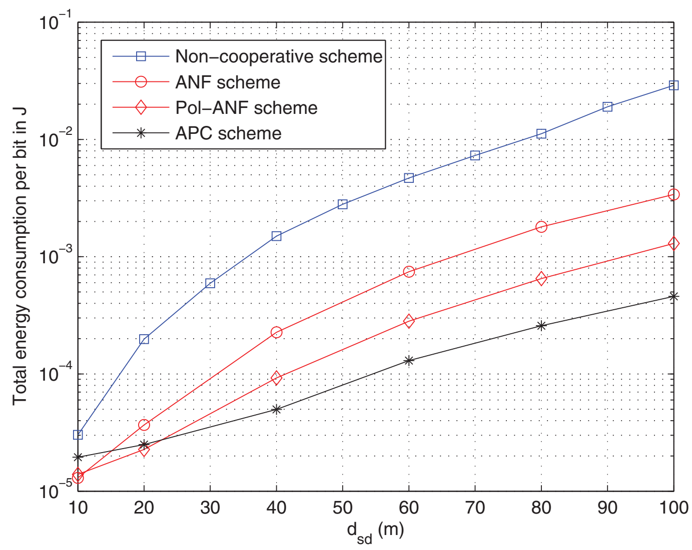

Fig. 10. Total energy consumption per bit over d_{sd} when the relay node is located midway between source and destination nodes.

5. Conclusion

In this chapter, we discuss some of the major asynchronous cooperative communication protocols that can be used in vehicle-to-vehicle cooperative communications. The APC scheme with full duplex relay that completes the data transmission between the source and the destination in approximately same time duration as non-cooperative scheme is discussed in detail. The performance improvement of APC scheme is demonstrated by the BER and the capacity simulation results, which show its superiority over non-cooperative, conventional and polarized ANF protocol. Even with the use of more RF front ends, the APC scheme has less total energy consumption than ANF and non-cooperative schemes over more practical distances between the nodes. Thus, the APC scheme is both spectral and energy efficient, and is suitable for inter-vehicle cooperative communication.

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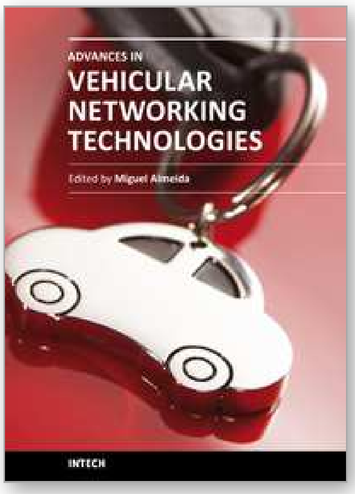

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This book provides an insight on both the challenges and the technological solutions of several approaches, which allow connecting vehicles between each other and with the network. It underlines the trends on networking capabilities and their issues, further focusing on the MAC and Physical layer challenges. Ranging from the advances on radio access technologies to intelligent mechanisms deployed to enhance cooperative communications, cognitive radio and multiple antenna systems have been given particular highlight.