Dispensing with Channel Estimation...

Low-Complexity Noncoherent Virtual MIMOs

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Mohammed El-Hajjar and Lajos Hanzo

In this article, we investigate the feasibility of noncoherent detection schemes in wireless communication systems as a low-complexity alternative to the family of coherent schemes. The noncoherent schemes require no channel knowledge at the receiver for the detection of the received signal, while the coherent schemes require channel inherently complex estimation, which implies that pilot symbols have to be transmitted resulting in a wastage of the available bandwidth as well as the transmission power. We begin with an overview of differentially encoded modulation followed by differentially encoded multiple-input multiple-output (MIMO) schemes. We continue by presenting the concept of double-differential schemes, which provide a good performance in the presence of carrier offset while dispensing with channel estimation. Additionally, we investigate the application of both single- and double-differential schemes in the context of cooperative communications. Explicitly, the differential schemes perform within a 3-dB margin from their coherent counterpart that is using perfect channel knowledge at the receiver. However, when the channel estimate at the receiver is inaccurate or unreliable, differentially detected schemes are capable of providing a better performance than their coherent counterpart.

Coherent Versus Noncoherent Communication Systems

The dramatic increase in demand for high-speed multimedia wireless services requires reliable and spectrally efficient wireless communication systems. This

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implies that the wireless systems are required to use the limited available bandwidth and power as efficiently as possible. The main challenge in wireless communication is the overcoming of the hostile nature of the channel, where signals propagate along different paths due to reflection, scattering, and diffraction from obstructing objects. So, the received signal becomes the sum of the different signal paths, which add either constructively or destructively. This makes channel estimation a challenging task, although its accuracy is crucial for correct detection of the data [1].

In practice, the channel-state information (CSI) of each link between each transmit and receive antenna pair has to be estimated at the coherent receiver either blindly or using training symbols [1]. Channel estimation invoked for all transmit and receive antenna pairs substantially increases both the cost and complexity of the receiver. When the CSI fluctuates dramatically from burst to burst, a high density of pilots is required to be transmitted, resulting in an undesirable wastage of both the bandwidth and the transmission power.

Alternatively, it is beneficial to develop low-complexity techniques that do not require any channel information at the receiver. Hence, differentially encoded transmission and noncoherent reception constitute a desirable design alternative that does not require the knowledge of the CSI. Therefore, noncoherent schemes save both the bandwidth and the power wasted by transmitting the pilot symbols, although this is achieved at the expense of a 3-dB performance loss in comparison to a system using coherent detection with perfect channel knowledge at the receiver. However, in practice, the channel impulse response (CIR) is never perfectly estimated at the receiver, and so channel estimation errors induce performance loss.

For a single-transmit antenna, it is well known that differential schemes, such as differential phase-shift keying (DPSK), can be demodulated without any channel estimation. Differential schemes have been widely used in practical communication systems. For example, in the terrestrial digital video broadcasting (DVB-T/T2), reference pilots, which are known at the receiver, are transmitted using DPSK before the broadcast data commences. The reference pilots are used for initial short-term channel estimation as well as for initial frequency- and time-synchronization. Star quadrature amplitude modulation (QAM) schemes [2] were designed for applying differential encoding to QAM constellations. The star QAM constellation does not have the maximum achievable free distance between the constellation points but does allow low-complexity differential encoding and decoding methods to be used, eliminating high-complexity channel estimation [2].

Another design alternative is to employ multiple-symbol-based detection [3] for reducing the performance loss of the differentially versus coherently detected schemes. A differential detection technique for multiple phase-shift keying was presented [3], where maximum-likelihood sequence estimation of the transmitted phases was employed rather than symbol-by-symbol detection as in the conventional differential detection. It has been shown that the multiple-symbol-based detection scheme performs better than the conventional differentially detected schemes, and it reduces the performance gap between the differentially and coherently detected systems [3].

NONCOHERENT SCHEMES SAVE BOTH THE BANDWIDTH AND THE POWER WASTED BY TRANSMITTING THE PILOT SYMBOLS.

To elaborate a little further, channel estimation becomes a more challenging task when more than one antenna are used at the transmitter and/or receiver. This is because the receiver has to estimate more than one CIR, and so more pilots have to be transmitted, resulting in wastage of more bandwidth and transmission power. Therefore, it is natural to consider extensions of differential schemes to MIMO systems. Tarokh and Jafarkhani [4] proposed a differential encoding and decoding technique for Alamouti's scheme [5] using real-valued phasor constellations; therefore the transmitted signal can be demodulated both with and without CSI at the receiver. The resultant differential detection-aided noncoherent receiver performs within 3 dB from the coherent receiver when assuming perfect knowledge of the CIR at the receiver. On a similar note, the concept of differential space-time spreading (DSTS) was introduced in [1] as a noncoherent MIMO scheme designed for achieving transmit diversity in code division multiple access systems, while supporting multiple users, where the transmitter can support two or four antennas, the receiver can be equipped with a variable number of antennas. A unified structure was proposed in [1] for describing all differential space-time block codes (DSTBCs), where the authors unify the structure of DSTBCs and propose the family of differential linear dispersion codes based on the so-called Caley transform, which is capable of simultaneously achieving both a high-throughput and a high-diversity gain.

In practical systems, a substantial carrier offset may be imposed by the mismatch between transmitter and receiver oscillators. This poses a challenge for the correct detection of the differentially encoded data, since differentially detected schemes rely on the assumption that the CIR taps remain constant over two consecutive symbols. More explicitly, the carrier offset transforms the slow-fading channel envelope into a more rapidly time-varying one, which implies that the CIR taps no longer remain constant over two symbol periods, which is a basic requirement for the correct detection of differentially encoded data. Hence, the so-called double-differential schemes [6]

CHANNEL ESTIMATION BECOMES A MORE CHALLENGING TASK WHEN MORE THAN ONE ANTENNA ARE USED AT THE TRANSMITTER AND/OR RECEIVER.

have been proposed, which are capable of performing well in the presence of carrier offsets.

Reliable wireless communications may not be guaranteed even when transmit diversity-aided MIMO schemes are used. This may be the case when large-scale shadow fading exists, imposing correlation on the different MIMO channels, unless the individual MIMO elements are sufficiently far apart. The concept of cooperative diversity [7] has been proposed in the literature as a technique providing diversity or throughput gains without the need for colocated MIMO elements. In cooperative communications, the difficulties of implementing antenna arrays in a shirt-pocket-sized mobile station (MS) can be avoided, where the single antenna of other MSs can be used as virtual MIMO antennas. Thus a single-input single-output (SISO) system can be transformed into a MIMO one. In cooperative communication systems, the first stage of communications is composed of the source transmitting data to both the relay and destination followed by the next stage where the relay transmits the user's data to the destination. This means that channel estimation has to be performed at both the relay and also at the destination for all the virtual MIMO elements. It is also beneficial to design noncoherent detectors that dispense with channel estimation at both the relay and the destination. In a differential cooperative system, it is not required that the nodes possess any information about the channels of the different links. Differential modulation designed for a cooperative system constituted by a relay-aided single-source destination pair was proposed in [8].

This contribution provides a light-hearted perspective on noncoherent wireless communications and demonstrates how differential detection can be invoked without any CSI at the receiver. In the "Differential Modulation" section, we elaborate on differential modulation schemes, including DPSK and star QAM. In the "Differential MIMO" section, we present the extension of the idea of differential modulation to MIMO systems, and then, we present the concept of double-differential coding in the "Double-Differential Schemes" section. The application of differential encoding designed for cooperative communications is discussed in the "Differential Cooperative Communications" section. Finally, we present the results and discussion and the conclusions.

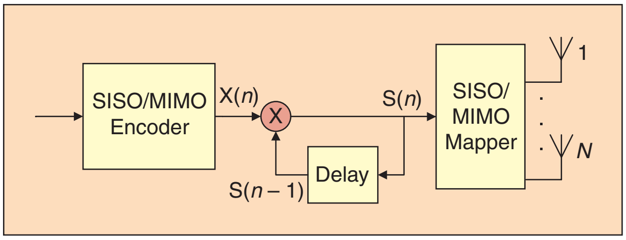

FIGURE 1 Block diagram of a single differential scheme.

Differential Schemes

In this section, we provide an overview of classic differentially encoded schemes used in SISO systems followed by a description of the evolution of differential detection designs for MIMO systems.

Differential Modulation

As mentioned in the earlier section, DPSK and star QAM do not require the knowledge of the CIR, although this is achieved at the expense of a 3-dB performance loss, compared with a system employing coherent modulation and assuming perfect channel knowledge at the receiver. However, when realistic channel estimation is performed, naturally, channel estimation errors are encountered, which results in a loss in the coherent systems' performance.

The block diagram of a differential encoder is shown in Figure 1 (in the case of SISO, the number of transmit antennas N in Figure 1 is equal to one), where a single antenna is used for transmitting the data. When DPSK and differential star QAM are used, the data bits are first mapped to the symbols $x(n)$ as in the coherent scheme, and then differential encoding is performed as follows. Assume that the differentially modulated symbol $s(n)$ is transmitted at time instant n, as shown in Figure 1. The differentially modulated symbol $s(n)$ at time instant n is obtained as $s(n) = x(n) \times s(n-1)$, as shown in Figure 1, where $x(n)$ is a PSK or star QAM-modulated symbol, and $s(n-1)$ is the differentially encoded symbol transmitted at time instant $n-1$.

The received signal at time instant n is $r(n) = h(n) \times s(n) + N(n)$, where h is the CIR between the transmitter and receiver, and the noise sample is $N(n)$ with a variance of σ_n^2. To detect the signal transmitted at symbol instant n, the receiver computes $r(n) \times r(n-1)^*$, where * represents the complex conjugate operation. Then, the receiver finds the legitimate symbol of the constellation closest to $r(n) \times r(n-1)^*$ as the estimate of the transmitted symbol.

In differential modulation, we assume that the CSI has not changed between two consecutive symbol periods. The associated phase change, if any, is purely owing to the modulating symbol. Since the previously detected symbol acts as a reference, an erroneous decision inflicts a second error, and this error-doubling translates to a 3-dB signal-to-noise ratio (SNR) difference between the coherently detected system using perfect CSI at the receiver and the differentially detected system.

Differential MIMO

Recently, MIMO systems have attracted substantial research interests because of their increased capacity compared with SISO systems. The advantages of MIMOs can be exploited in terms of their diversity gain, leading to an improved bit-error ratio (BER) performance and/or multiplexing gain, providing an increased data rate. However, channel estimation invoked for all the MIMO links substantially increases both the cost and complexity of the receiver, aggravated by the pilot-induced throughput reduction. When the CSI fluctuates dramatically from burst to burst, an increased number of training symbols has to be transmitted, potentially resulting in an undesirably high-transmission overhead and wastage of transmission power. Therefore, it is beneficial to develop low-complexity MIMO techniques that do not require any channel information and are thus capable of mitigating the complexity of MIMO-channel estimation.

The block diagram of a general differential scheme is shown in Figure 1 (for MIMO systems, the number of transmit antennas N in Figure 1 is strictly greater than one), where the data bits are first mapped to symbols. Then, the data symbols are encoded according to the MIMO scheme used, such as Alamouti's STBC [5]. Afterward, differential encoding is performed by multiplying the MIMO encoded block hosted by the vector $\mathbf{x}(n)$ at time instant n with the transmitted block $\mathbf{S}(n-1)$ at time instant $(n-1)$ as shown in Figure 1.

A noncoherent detection algorithm designed for Alamouti's scheme [5] was proposed in [4], where the authors proposed a differential encoding and decoding technique for Alamouti's scheme [5] using real-valued phasor constellations. The differential scheme of [4] was restricted to PSK modulation, which was extended to QAM constellations in [9]. The differential decoding in MIMO systems is similar to that of classic differential modulation in SISO systems in the sense that the receiver uses the data received in two consecutive time slots for decoding the received signal. DSTBC schemes designed for MIMOs were proposed in [10] for real-valued constellations. Afterward, Hwang et al. [9] developed a DSTBC scheme that supports nonconstant modulus constellations combined with four transmit antennas. This extension, however, requires the knowledge of the received power to appropriately normalize the received signal. The received power was estimated blindly using the received differentially encoded signals without invoking any channel estimation techniques or transmitting any pilot symbols. The concept of DSTS was proposed [1] as a noncoherent MIMO scheme supporting multiple users, where the transmitter can support two or four antennas, whereas the receiver can be equipped with a variable number of antennas.

The differential MIMO schemes, mentioned earlier focus on systems aiming at achieving a high-spatial diversity gain and hence attaining an improved BER performance. However, a differential scheme based on a spatial multiplexing approach, such as the Bell-Labs layered space time wireless architecture, was proposed [11]. This architecture provides a multiplexing gain, given that the number of receive antennas is at least equal to that of the transmit antennas, without the need for channel estimation. In [11], a symbol mapping method was developed to avoid the amplitude variation of the transmitted signals, which can also improve the systems' performance while employing a trellis-based decoder. This differential scheme may significantly reduce the systems' complexity, since it avoids the need for channel estimation.

Additionally, orthogonal frequency division multiplexing (OFDM) is a widely used technique, which can be combined with MIMOs for attaining the MIMO gains in frequency selective channels. Again, channel estimation is a crucial task for reliable communication, where the channel is time- and frequency-variant, and thus sophisticated channel estimation techniques are required. Additionally, in strongly frequency-selective and rapidly fading mobile channels, substantial channel estimation errors are incurred, which results in a considerable performance loss. In such scenarios, differential encoding and detection without the need for CSI becomes an attractive alternative. In [12], a differential coding scheme was proposed for MIMO–OFDM systems, where differential encoding was performed both versus time and frequency. By contrast, a differential MIMO–OFDM technique was proposed [13], where differential encoding was applied versus space and frequency. The slower the channel fluctuation in a specific domain, the lower is the differential detection loss.

Double-Differential Schemes

The differential schemes described in the earlier section assume the channel to be stationary over two consecutive symbols, in order for the data to be correctly differentially decoded. However, when the transmitter or receiver are in motion or when there is a mismatch between the oscillators at the transmitter and the receiver, the assumption of a stationary channel remains no longer valid; therefore the performance of the differential systems substantially degrades.

In practical systems, carrier offset is a crucial problem, which renders the implementation of differential schemes challenging. Therefore, double-differential schemes [6] were proposed as an extension of differential schemes for systems where substantial carrier offset is present.

A block diagram of the double-differential encoder is shown in Figure 2, where an additional delay stage is added to the classic single-differential scheme. Thus in double-differential schemes, the transmitted signal at time instant n is $\mathbf{V}(n) = \mathbf{X}(n) \times \mathbf{S}(n-1) \times \mathbf{V}(n-1)$, where $\mathbf{X}(n)$ is the coherently encoded signal at symbol instant n, $\mathbf{S}(n-1)$ is the differentially encoded signal at symbol instant $(n-1)$ and $\mathbf{V}(n-1)$ is the double-differential encoded signal transmitted at symbol instant $(n-1)$. Therefore, in double-differential decoding, the decoder

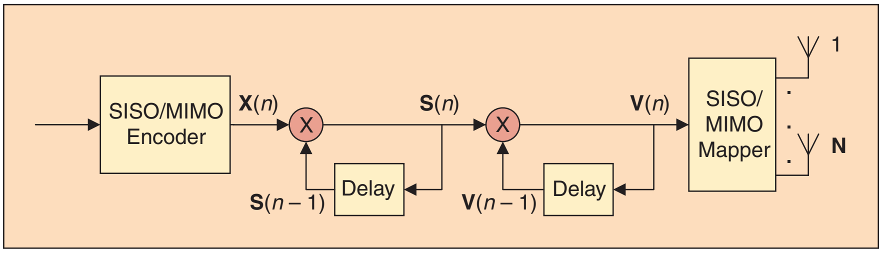

FIGURE 2 Block diagram of a double-differential scheme.

requires the data received in three consecutive symbol periods to decode the current signal.

Differential Cooperative Communications

A stylized cooperative communications system [7] is shown in Figure 3, where two stages of communication are employed. During the first stage, the source transmits its information to the destination and the relay. Then, in the second stage of cooperation, the relay retransmits the source data to the destination. Hence, the destination has two replicas of the source data, which results in a diversity gain and an improved BER performance, although this is achieved at the expense of a throughput loss, since the data are transmitted in two time slots.

When coherent communications is employed, both the destination and relay has to estimate the channel in the first stage of cooperation. Additionally, during the second stage of cooperation when the relay transmits its data to the destination, the destination has to estimate the CIR between the relay and destination. This requires substantial signaling, leading to a significant loss in the available bandwidth, which makes the extension of differential encoding to cooperative communications an important one. Differential modulation designed for amplify-and-forward (AF) cooperative systems was proposed [8], where the source transmits its data using DPSK. The relay retransmits its received data to the destination using differential modulation. The data received from both the source and relay can then be decoded at the destination with differential maximum-likelihood decoding using the data received in four time slots, where two time slots are required for the transmission of the same data from the source and then from the relay in a time division multiple access (TDMA) fashion, i.e., the source and relay transmit in different time slots.

A differential scheme based on the STBC design of [5] was proposed [14]. A cooperative system consisting of two cooperating users and a single destination was considered, where the two users act as relays for each other. The cooperative transmission scheme proposed [14] employs three time slots for the transmission of a single symbol for each user, i.e., two symbols are transmitted in three time slots. During the first time slot, user 1 differentially encodes his/her data and transmits the differentially encoded data x_1 to user 2 as well as to the destination. In the second time slot, user 2 differentially encodes his/her data x_2 which is transmitted to both user 1 and to the destination. Finally, during the third time slot, user 1 differentially encodes the estimated data of user 2 $\hat{x}_2$ and transmits a negative and conjugated version of it $-\hat{x}_2^*$ to the destination. Also, during the third time slot, user 2 differentially encodes the estimated data of user 1 $\hat{x}_1$ and transmits a conjugated version of it $\hat{x}_1^*$ to the destination. The differential decoder of [14] uses the data received during six time slots for decoding the data received during the current symbol period.

Albeit they achieve a diversity gain at the expense of a reduced throughput, cooperative communication systems are more vulnerable to carrier frequency offset (CFO) than colocated MIMO systems, since the source, relay, and destination may be moving and the oscillators of the three terminals can never be perfectly matched. In the presence of carrier offset, differential encoding designed for cooperative communications may fail to attain the required performance. Hence, it was proposed in [15] to use double-differential modulation for cooperative communications, where the system attains a good performance in the presence of carrier offset while dispensing with channel estimation. In [15], the authors proposed to employ double-differential modulation for the AF scheme in a TDMA fashion. The source double-differentially modulates its data, which is transmitted to the relay and destination in the first time slot. During the second time slot, the relay amplifies the received signal and transmits it to the destination. The destination then decodes the received data using an emulated maximum ratio combining scheme for decoding the signal received from the source and relay without any channel knowledge.

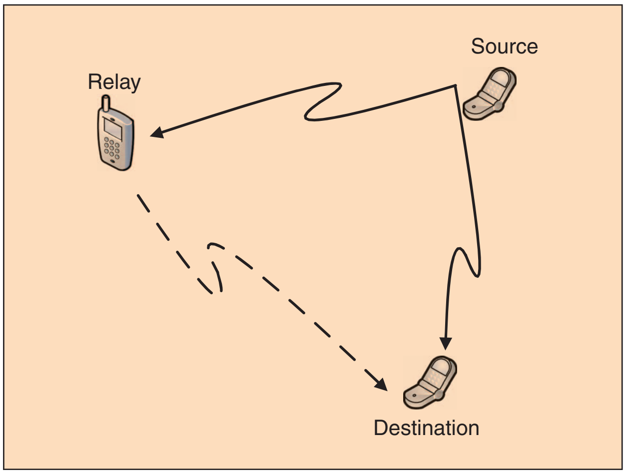

FIGURE 3 Cooperative communications system.

Results and Discussion

In Table 1, we present the density of pilot symbols in the DVB second-generation terrestrial TV (DVB-T2). In DVB-T2, there are several types of pilots used for channel and noise estimation, as well as for frequency and time synchronization. The required pilot's density is directly related to the channel characteristics. For example, in a fast-fading channel, a high density of pilots is required for channel estimation, whereas in a slow-fading channel, lower-density pilots can be used. In Table 1, we show the pilot density for different OFDM symbol sizes and for different pilot patterns (PP), PP1 to PP8. An empty entry in Table 1 means that the PP and the fast Fourier transform (FFT) size combination is not used. Observe in Table 1 that, for PP1, the pilot density is the highest, and it decreases as the PP order increases up to PP8. As the density of pilots decreases, the available bandwidth and power will be used in a more efficient way, since less pilots are transmitted, and so more data can be communicated. However, transmitting less pilots results in the channel estimation being less accurate, hence resulting in more detection errors and a degraded performance.

To study the effect of channel estimation errors on the performance of coherently detected systems, we present a comparison between the BER performance of the DSTS [1] and its coherent counterpart, where we model the channel estimation error by imposing additive white Gaussian noise on the channel information at the receiver side. Although the channel estimation error does not accurately obey a Gaussian distribution, this simplified investigation gives us an insight concerning the effects of channel estimation errors on coherent systems. Figure 4 compares the BER performance of the DSTS and the space-time spreading (STS) schemes using two transmit antennas, one receive antenna and binary phase shift keying (BPSK) modulation. As discussed previously, coherent systems assuming perfect CSI at the receiver outperform their differentially encoded, noncoherently detected counterpart by about 3 dB. However, as shown in Figure 4, when we add noise to the CSI used by the coherent STS scheme, we see that the performance degrades. More quantitatively, Figure 4 shows that, when the power of the channel estimation noise added to the CSI is increased and hence the corresponding CSI SNR is 20 dB or less, the performance of the coherent STS scheme tends to exhibit an error floor and its BER curve crosses the BER curve of the DSTS scheme. Beyond this crossover point, the DSTS outperforms the STS. Therefore, the DSTS constitutes a convenient and low-complexity design, alternative to the coherent STS scheme, since the DSTS scheme eliminates the complexity of channel estimation and also results in a potentially better performance when the channel estimation error is high. Explicitly, if we consider a DVB-T2 system transmitting over a fading channel associated with the normalized Doppler frequency of 0.1 then using the PP1 of Table 1 facilitates the acquisition of a relatively accurate channel estimate, which results in a better BER performance for the coherent system than that of its noncoherent counterpart. However, the pilot density of PP1 is high, which wastes about 10% of the available bandwidth, whereas the noncoherent scheme uses the full available bandwidth. It is worth noting that, in all fairness, the corresponding BER curve should be commensurately shifted to the right, as we would classically do for the same amount of forward error correction (FEC) coded redundancy. Additionally, the pilot symbols can be inserted before FEC coding, which was exploited in [16] to improve the achievable performance. Finally, the performance loss of differential encoding was significantly reduced in [17] at the cost of an increased complexity, which was then reduced using sphere detection. On the other hand, a system employing PP8 of Table 1, where the pilot density is low, attains a high channel estimation error in a fading channel having a normalized Doppler frequency of 0.1, which leads to the error floor in the BER curve seen in Figure 4. Therefore, according to the results of Figure 4, it

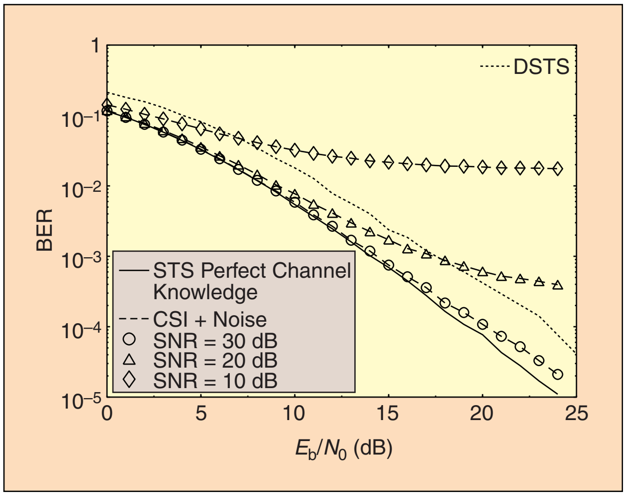

FIGURE 4 Performance comparison of a differentially encoded noncoherent system with its coherent counterpart while considering channel estimation error.

TABLE 1 *Density of pilot symbols in the DVB-T2 data signal.*

	Pilot Pattern							
FFT Size	*PP1 (%)*	*PP2 (%)*	*PP3 (%)*	*PP4 (%)*	*PP5 (%)*	*PP6 (%)*	*PP7 (%)*	*PP8 (%)*
1,024	10.45	9.96	6.45	5.75	4.1			
2,048	10.73	10.15	6.4	6.05	4.28		3.46	
4,096	9.54	9.3	5.3	5.13	3.25		2.5	
8,192	8.93	8.845	4.75	4.67	2.68		1.75	1.75
16,384	8.91	8.78	4.73	4.63	2.65	2.53	1.6	1.66
32,768		8.725		4.55		2.47	1.6	1.66

becomes clear that differential schemes constitute a low-complexity design alternative that does not require any channel estimation and may result in a better performance than the coherently detected systems in the presence of imperfect channel estimation.

Conclusions

In this article, a comparison of coherent and noncoherent transmission schemes was presented, where the noncoherent receivers do not require CSI to decode the received signal. On the other hand, coherent receivers require the CIR to decode the received signal, where the CIR can be acquired by transmitting pilot signals resulting in wastage of the available bandwidth as well as the transmission power. Differential modulation, including DPSK and differential star QAM, can be demodulated without requiring any channel knowledge at either the transmitter or receiver. Additionally, the concept of differential decoding has been extended to MIMO systems, where the channel estimation complexity increases with the number of transmit and receive antennas. In the presence of CFO, differential schemes fail to decode the received signal reliably, and so the idea of double-differential schemes was shown to provide a reliable detection while dispensing with channel estimation. With the introduction of cooperative communications, it is natural to consider noncoherent cooperative communication schemes, where the evolution of differential cooperative communications has been presented. Finally, we quantified the bandwidth loss due to employing pilots in the DVB-T2 system, where a low pilot density might result in a high-performance loss in a fast-fading channel, hence potentially allowing the noncoherent differential receiver outperforming its coherent counterpart.

Author Information

Mohammed El-Hajjar received his B.Eng. degree in electrical engineering from the American University of Beirut in 2004. He received his M.Sc. degree in radio frequency communication systems and Ph.D. degree from the University of Southampton in 2005 and 2008, respectively. He is with Imagination Technologies Ltd., Chepstow, United Kingdom, as a design engineer, where he is working on DVB-T2/NGH transceiver design. He is the recipient of several academic awards and has published a Wiley-IEEE book and more than 35 journal and international conference papers. His research interests include coding and modulation, MIMO transceiver design, and cooperative communications.

Lajos Hanzo (lh@ecs.soton.ac.uk) received his degree in electronics in 1976 and his doctorate in 1983. During his 34-year career in telecommunications, he has held various research and academic posts in Hungary, Germany, and the United Kingdom. Since 1986, he has been with the School of Electronics and Computer Science, University of Southampton, United Kingdom, where he is the chair for telecommunications. He has coauthored 19 Wiley-IEEE Press books on mobile radio communications and published 850 research articles and book chapters. He served as a TPC chair of IEEE conferences, presented keynote lectures, and has been awarded a number of distinctions. He is a Fellow of the IEEE. Currently, he is directing an academic research team, working on a range of research projects in the field of wireless multimedia communications sponsored by the industry, the Engineering and Physical Sciences Research Council (EPSRC), United Kingdom, the European IST Program, and the Mobile Virtual Centre of Excellence (VCE), United Kingdom. He is an enthusiastic supporter of industrial and academic liaison and offers a range of industrial courses. He is an IEEE Distinguished Lecturer as well as a Governor of both the IEEE ComSoc and the VTS. He is the editor-in-chief of the IEEE Press and a chaired professor at Tsinghua University, Beijing.

References

[1] L. Hanzo, O. Alamri, M. El-Hajjar, and N. Wu, *Near-Capacity Multi-Functional MIMO Systems: Sphere-Packing, Iterative Detection and Cooperation*. Chichester, U.K.: Wiley-IEEE, May 2009.
[2] W. T. Webb, L. Hanzo, and R. Steele, "Bandwidth efficient QAM schemes for Rayleigh fading channels," in *IEE Proc. Communications, Speech and Vision*, June 1991, vol. 138. pp. 169–175.
[3] D. Divsalar and M. K. Simon, "Multiple-symbol differential detection of MPSK," *IEEE Trans. Commun.*, vol. 38, pp. 300–308, Mar. 1990.
[4] V. Tarokh and H. Jafarkhani, "A differential detection scheme for transmit diversity," *IEEE J. Select. Areas Commun.*, vol. 18, no. 7, pp. 1169–1174, 2000.
[5] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, 1998.
[6] M. K. Simon and D. Divsalar, "On the implementation and performance of single and double differential detection schemes," *IEEE Trans. Commun.*, vol. 40, pp. 278–291, Feb. 1992.
[7] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inform. Theory*, vol. 49, no. 10, pp. 2415–2425, 2003.
[8] Q. Zhao and H. Li, "Performance of differential modulation with wireless relays in Rayleigh fading channels," *IEEE Commun. Lett.*, vol. 9, pp. 343–345, Apr. 2005.
[9] C.-S. Hwang, S. H. Nam, J. Chung, and V. Tarokh, "Differential space time block codes using nonconstant modulus constellations," *IEEE Trans. Signal Processing*, vol. 51, no. 11, pp. 2955–2964, 2003.
[10] H. Jafarkhani and V. Tarokh, "Multiple transmit antenna differential detection from generalized orthogonal designs," *IEEE Trans. Inform. Theory*, vol. 47, no. 6, pp. 2626–2631, 2001.
[11] L.-Y. Song, A. G. Burr, and R. C. de Lamare, "Differential Bell-labs layered space time architectures," in *Proc. IEEE Int. Conf. Communications*, June 2007, pp. 5093–5097.
[12] V. Pauli, L. Lampe, and J. Huber, "Differential space-frequency modulation and 2D-detection for MIMO-OFDM," in *Proc. IEEE Int. Conf. Communications*, June 2007, pp. 5412–5418.
[13] E. Haas and S. Kaiser, "Two-dimensional differential demodulation for OFDM," *IEEE Trans. Commun.*, vol. 51, pp. 580–586, Apr. 2003.
[14] P. Tarasak, H. Minn, and V. K. Bhargava, "Differential modulation for two-user cooperative diversity systems," *IEEE J. Select. Areas Commun.*, vol. 23, pp. 1891–1900, Sept. 2005.
[15] M. R. Bhatnagar, A. Hjorungnes, and L. Song, "Cooperative communications over flat fading channels with carrier offsets: A double-differential modulation approach," *EURASIP J. Adv. Signal Process.*, vol. 2008, no. 531786, pp. 1–11, 2008.
[16] N. Bonello, S. Chen, and L. Hanzo, "Pilot symbol assisted coding," *Electron. Lett.*, vol. 45, pp. 518–519, May 2009.
[17] L. Wang and L. Hanzo, "The amplify-and-forward cooperative uplink using multiple-symbol differential sphere-detection," *IEEE Signal Processing Lett.*, vol. 16, pp. 913–916, Oct. 2009.

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