ACHIEVING MOBILITY FOR DVB-T BY SIGNAL PROCESSING FOR DOPPLER COMPENSATION

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ABSTRACT

The reception of a DVB-T signal is significantly affected if the channel is rapidly changing, as for instance in a moving car. As a result, existing equipment that is suited for static reception does not guarantee the necessary link quality for speeds beyond 30 km/h. In order to achieve higher speeds, most of the current solutions propose to use two antennas at the receiver and a more elaborate signal processing method for channel tracking. In this paper we consider a signal processing technique that specifically addresses the time-varying nature of the channel and allows to reach speed beyond 100 km/h on a receiver equipped with a single antenna in the relatively adverse condition of a Rayleigh fading. The proposed scheme performs the cancellation of the self-interference caused by the channel variations and imperfect channel estimation. The building blocks of the new algorithm have been optimised in order to reduce the complexity. A combination of both the new signal processing technology and the use of two antennas at the receiver has also been considered, in order to achieve high speed also for the configurations of the DVB-T which are most affected by mobility. Simulations show that the use of the new signal processing yields a significant improvement in terms of maximum speed that can be reached with an appropriate QoS.

INTRODUCTION

The Digital Video Broadcasting (DVB) standard was originally devised for the reception of video content at a rate of up to 5 MBits/sec in a home environment. More recently, the interest arose on the use of DVB-T receivers in moving cars in order to deliver video as well as other digital data that can be allocated on the available spectrum. These new applications are a promising opportunity, and may represent a strong competitive advantage for any terrestrial broadcaster, while satellite and cable DVB may be predominant for static (home) reception. In this respect, the ability of the existing DVB-T standard to ensure good quality reception for mobile applications is also a relevant issue in the comparison with other competing digital video broadcasting standards.

However, the mobile reception of a high bit-rate signal is a challenging task for DVB-T, since it employs the Orthogonal Frequency Division Multiplexing (OFDM) as modulation technique. Here, data are divided into many parallel streams and each stream is modulated on a different sub-carrier frequency. The block-processing structure of OFDM yields proper reception only if the channel is sufficiently time-invariant at least for the duration of one block. If this condition is not satisfied and the channel changes during the transmission of each block, then self-interference arises among the different sub-carriers (inter-carrier interference, ICI).

Various solutions to counteract the effects of ICI have been proposed. Longer time interpolators are useful for a better estimate of the channel, as shown by Espineira and

Stare (1). Also multiple antennas at the receiver yield a diversity gain, see Faria (2), that overcomes partially the performance loss. However, both solutions have important drawbacks, since the interpolators require more silicon area for memory, while the use of multiple antennas lead to additional cost due the extra equipment and its deployment. Meanwhile, current solutions based on one antenna are exceedingly complex for the DVB-T. Jeon, Chan and Cho (3) proposed a linear equalisation scheme, which requires operations with high complexity. In order to reduce the complexity, new schemes have been proposed by Gorokhov and Linnartz (4-5). These schemes are based on the idea of estimating the channel parameters and performing a cancellation of the interference, but their application of these schemes to the existing DVB-T standard is not straightforward. In fact a training sequence was used in order to estimate the channel parameters, which is not present in DVB-T standard. Moreover, when sub-optimal channel estimators are considered, for high constellation and high speed the schemes do not guarantee the necessary QoS.

Next, we propose new schemes for both the interference cancellation and the channel parameter estimation. In order to reduce the complexity we propose an efficient scheme for the estimation of the channel parameters. The required QoS can be reached for higher speeds by applying iteratively the estimation of the channel and the interference cancellation. The main advantages of the proposed systems are:

- a higher speed at which the DVB-T reception is correct,
- a complexity similar to the previously-proposed two antennas system,
- the possibility to be used on a two antenna system, with additional benefits.

Simulations results are presented for various modes, constellation sizes and code rates of the DVB-T standard. By comparing the performance of the schemes with reduced complexity against existing solutions with multiple antennas, we conclude that the new techniques allow the use of DVB-T for similar or higher speeds range with a limited complexity.

INTERFERENCE CANCELLATION AND CHANNEL ESTIMATION

System model

In a OFDM transmitter, the high-rate symbol data stream is divided into blocks of N symbols, each of which is to be transmitted on a different subcarrier. In fact, an inverse Discrete Fourier Transform (IDFT) transforms the (frequency-domain) data symbols into the transmitted time-domain signal. Before being transmitted, the signal is extended cyclically, so that for each extended block the last L samples are replicas of the first L samples. At the receiver, the cyclic extension is removed and a DFT is applied on block of size N. If the channel is moderately dispersive, the samples on each sub-carrier will be the product of the data symbols and a complex constant depending on the channel transfer function. The insertion of the cyclic prefix and the cascade of DFT and IDFT transform the dispersive channel into a set of parallel flat channels, each operating at a low rate. This is well recognised as an advantage and it explains the popularity of OFDM.

When the channel is time-varying, such as in mobile reception, the OFDM transceiver is not anymore equivalent to a set of parallel flat-fading channels, but data on one sub-carrier leaks to other sub-carriers, thus generating inter-carrier interference (ICI). Note that the ICI is determined both by the channel and by the data.

In its simplest version, the signal on each sub-carrier can be expressed as the sum of two contribution. The first term is the product of the wanted data transmitted on the corresponding sub-carrier and the channel transfer function. The second term reflects the ICI contribution, and can be estimated as a (truncated) Taylor-series expansion of the complete ICI. By indicating with **d** the transmitted data vector containing *N* data symbols, with **y** the vector of the received symbols after the DFT, the input/output relation can be approximated as

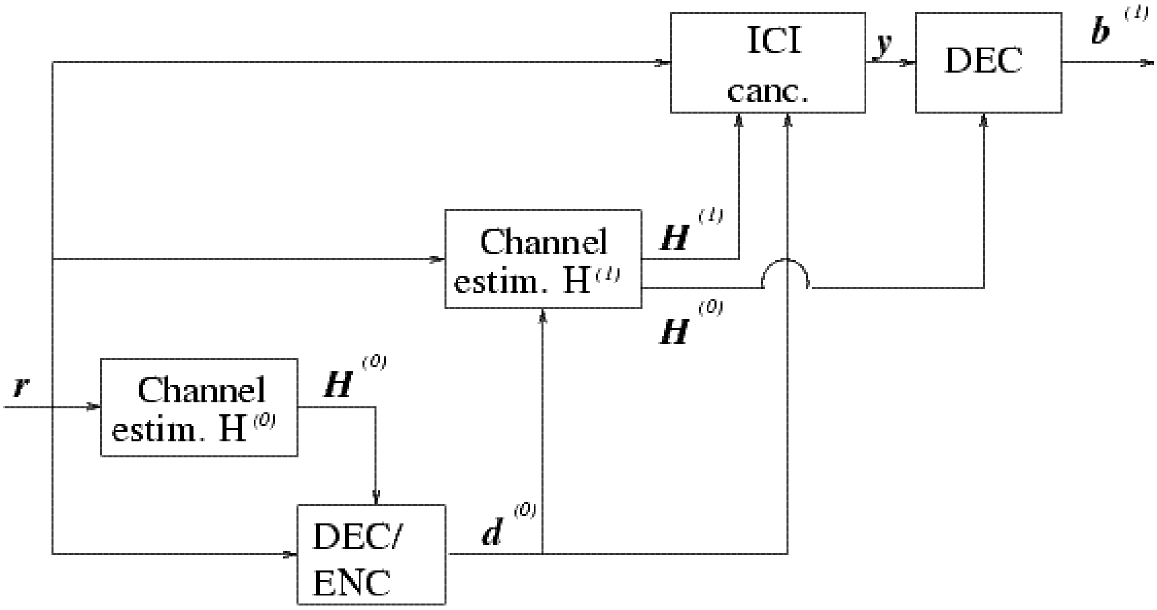

Figure 1 – ICI cancellation scheme

$$\mathbf{y} \approx \mathbf{H}^{(0)} \cdot \mathbf{d} + \mathbf{A}\mathbf{H}^{(1)} \cdot \mathbf{d} + \mathbf{n}$$

where · denotes the element-wise product between vectors, $\mathbf{H}^{(0)}$ and $\mathbf{H}^{(1)}$ are vectors describing on the channel amplitude and temporal changes (derivatives) thereof, respectively. **A** is a fixed matrix and **n** is the noise term. Note that the first term accounts for the static part of the channel and gives the contribution of the useful signal. In the second part, the matrix **A** has (only) off-diagonal terms which account for the ICI.

When a training sequence is present in the transmitted signal, the estimation of the channel parameters $\mathbf{H}^{(0)}$ and $\mathbf{H}^{(1)}$ can be performed simply, as shown by Gorokhov and Linnartz (4). However, in the DVB-T standard the training sequence is not available and we derived a new scheme that is suitable for the existing DVB-T standard allows the estimation of the parameters. Moreover, in order to increase the maximum speed at which the system can work, we exploited the error correction capabilities provided by the codes of the DVB-T standard and we iteratively improve the reliability of the data and the channel estimate.

Figure 1 shows the complete block diagram of the simplified Doppler compensation scheme. The received signal **r** is first used to perform a channel estimation of $\mathbf{H}^{(0)}$. This estimation is based on the pilot tones and it is averaged with a predicted estimation, as described in the next Section. In order to obtain a good estimate for the data, the error correction capabilities that are present in the DVB-T standard are used. In the block *DEC/ENC* the received signal is decoded and re-encoded in order to reduce the errors on the data and the obtain symbol stream $\mathbf{d}_0$ is used for the ICI cancellation. An estimate of the of the channel $\mathbf{H}^{(1)}$ is obtained with the block *Channel estim.* $H^{(1)}$, whose internal operations are explained in the next

Section. The ICI is removed through the block *ICI canc.* Lastly, the ICI-free signal **y** is decoded, to obtain the bit stream $\mathbf{b}_1$. In the ICI cancellation block the matrix multiplication $\mathbf{AH}^{(1)}\mathbf{d}$ is efficiently implemented through a FFT and a IFFT, see Gorokhov and Linnartz (5).

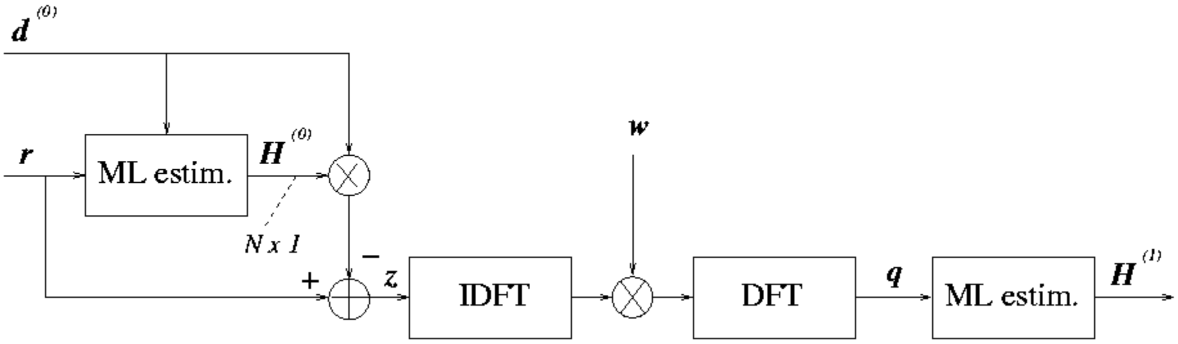

Figure 2 – Channel estimation block

The channel estimation

For the ICI cancellation, the channel parameters $\mathbf{H}^{(0)}$ and $\mathbf{H}^{(1)}$ must be estimated in order to properly cancel the interference. Previous analysis on the performance of DVB-T for mobile applications presented by Faria (2) have shown that the channel parameters should be estimated more accurately than for static applications, because of the fast-varying nature of the channel. The system considered in that study did not include the ICI modelling and in order to improve the channel estimation a longer time interpolator of the pilot symbols was used.

The use of our model yields two main differences with respect to the classical approach. First, a new estimator is needed to estimate $\mathbf{H}^{(1)}$. Secondly, since the new model gives a more detailed description of the channel variations, it is possible to predict the characteristics of the channel from block to block by using the knowledge of $\mathbf{H}^{(1)}$. This prediction ability improves the reliability of the estimate at a low implementation complexity.

The channel estimation block is shown in Figure 2. It is divided into two sections, for the estimation of $\mathbf{H}^{(1)}$ and $\mathbf{H}^{(1)}$, respectively. Note that in this case the ML estimation is performed separately for $\mathbf{H}^{(0)}$ and $\mathbf{H}^{(1)}$, thus requiring a significantly reduced complexity, with respect to the estimator of Gorokhov and Linnartz (4). From the received signal $\mathbf{H}^{(0)}$ is first estimated obtained by using the decided data symbol $\mathbf{d}^{(0)}$ as a training sequence and performing a ML estimation. Then the contribution of the $\mathbf{H}^{(0)}\mathbf{d}^{(0)}$ is subtracted from the received signal to obtain the interference contribution vector $\mathbf{z} \approx \mathbf{A}\ \mathbf{H}^{(1)}\mathbf{d}^{(0)}$. In order to estimate $\mathbf{H}^{(1)}$ $\mathbf{z}$ is multiplied by $\mathbf{A}^{-1}$, (or a MMSE inversion), to obtain **q**. The multiplication by $\mathbf{A}^{-1}$ is efficiently implemented by means of a IDFT, a element-wise product of the resulting vector and a constant vector **v** and lastly a DFT. Lastly, a ML estimator is applied to **q**. This estimator compute the channel parameters which have the highest probability, given the received **q** and the data **d**.

Predictive estimator

From Figure 1 we observe that one of the most critical blocks is *Channel estim.* $H^{(0)}$, since it performs a channel estimate based on pilot symbols which are strongly affected by the ICI. This problem has been pointed out also with standard receivers, that do not includes the ICI cancellation. Even when two antennas are used, a more elaborate channel estimation is needed in order to track the fast-varying channel. Here we propose an alternative method, that does not requires extra storage, but it exploits the knowledge on the evolution of the channel. An approximated prediction of $\mathbf{H}^{(0)}$ can be obtained by the values of $\mathbf{H}^{(0)}$ and $\mathbf{H}^{(1)}$ of the previous block, simply as $\mathbf{H}^{(0)} = \mathbf{H}^{(0)} + \mathbf{H}^{(1)}$. Moreover, for the average the more reliable value of $\mathbf{H}^{(0)}$obtained from the block *Channel estim.* $H^{(1)}$ is used. The increased reliability of the estimate yields more reliable decisions $\mathbf{d}^{(0)}$ and an higher speed at which the system can work.

Iterative scheme

In order to obtain a better performance, the signal processing of Figure 1 is iterated more times. Initially, the vector $\mathbf{b}^{(1)}$ of Figure 1 is re-encoded and mapped to obtain $\mathbf{d}^{(1)}$. Then, $\mathbf{d}^{(1)}$ is used instead of $\mathbf{d}^{(0)}$ in the next iteration: the channel estimation and the ICI cancellation are repeated and since now $\mathbf{d}^{(1)}$ is more reliable than $\mathbf{d}^{(0)}$, the errors on the decided symbols as well as on the channel parameters will be reduced. The iteration process can be applied more times, but we have seen that usually by using more than three iterations does not give any significant performance improvement.

Two antennas implementation

As shown in the next Section, by using the ICI cancellation scheme speeds up to 120 km/h can be reached for the highest bit-rate configuration of DVB-T. Two or more antennas can be used at the receiver, in order to increase the reliability of the received signal by means of signal combining. In this architecture a separate channel estimation and ICI cancellation is performed for the two received signals. However, whenever a decision is taken, the soft data signals from the two antennas are combined by maximum ratio combining (MRC), in order to gain from the diversity. The MRC is done twice: the first time after the estimation of $\mathbf{H}^{(0)}$ of the channel, in order to improve the first tentative decision. The second time is after the separate ICI cancellation, before the final decision on the data is taken.

SIMULATION RESULTS

We consider various configurations of the DVB-T transmission, including the block size (2K and 8K), the constellation size (QPSK, 16-QAM and 64-QAM) and the code rate (1/2, 2/3 and 3/4). The channel model is a Rayleigh channel with exponential decaying power profile having a root mean square delay spread of $\tau = 1.1$ ms and a maximum delay of 7 ms. This model approximates the Typically Urban (TU6) defined by the COST 207 project for GSM (6). For the time variation of the channel we used the model described by Jakes (7). When multiple antennas are considered, the transmission channels are generated independently.

In order to compare the performance of the various solutions to the interference generated by mobility, we considered the maximum speed at which the QoS constraints are satisfied, so that a proper reception of the signal is possible. As QoS target, we considered the bit error rate at the input of the decoder, and we derived them from the test lab results obtained for the Motivate project, see Faria (2).

Maximum attainable speed

A first set of simulation results show the maximum speed at which the DVB-T receiver can work on channel CH40 (626 MHz), with a bandwidth of 8 MHz. The overall band for analogue TV is between 400 and 790 MHz, so that the considered channel is roughly in the middle of the spectrum. Since the effect of mobility is stronger at higher frequency, this choice gives an average behaviour.

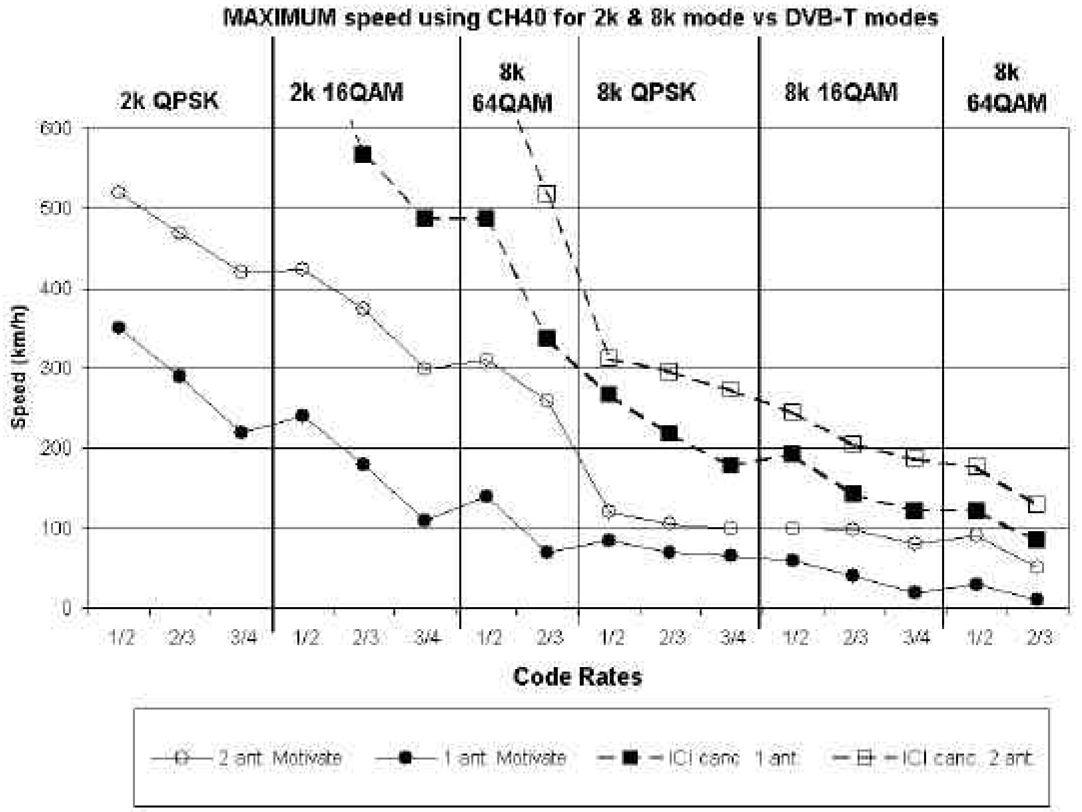

Figure 3 – Maximum achievable speed for various schemes.

Figure 3 shows the maximum speed that can be reached by the DVB-T system adopting different modes and constellations for the following equalization/estimation modes:

- *Continuos line, black circles* -- One antenna, standard equalisation and channel estimation methods (no ICI cancellation), compare Figure 8 of Faria G. (2).
- *Continuos line, empty squares* -- Two antennas with maximum ratio combining, standard equalisation and channel estimation methods (no ICI cancellation), compare Figure 8 of Faria G. (2).
- *Dashed line, black squares* -- One antenna with iterative ICI cancellation, 1 iteration, error correction, Taylor coefficients estimation in the loop.
- *Dashed line, empty squares* – Two antennas with ICI cancellation, no error correction, Taylor coefficients estimation by training sequence. Using a training sequence the channel estimator is performing better.

	# Ant.	# iterations	Max speed range (km/h) 1/2 rate code	Max speed range (km/h) 2/3 rate code
Standard DVB	1	1	18-38	6-12
2 ant. adv. ch. est.	2	1	76-150	31-63
ICI canc.	1	1	76-150	55-109
ICI canc.	2	1	80-160	76-161
ICI canc.	3	1	120-239	87-173
ICI canc. (2 ant.)	2	1	111-220	82-163

Table 1 – Maximum speed range for 64-QAM @ 8k.

	# Antennas	Silicon area (# FFT)
Standard DVB	1	9
2 ant.	2	20
2 ant. adv. ch. est.	2	60
ICI canc.	1	50
ICI canc. (2 ant.)	2	100

Table 2 – Complexity of various solutions.

From Figure 3 we see that the ICI cancellation scheme performs always better than the two antennas system. Most of current interest is focused on the 8k mode, since it allows an efficient deployment of Single Frequency Networks. On the other hand, higher constellation sizes as well as lower code rates are preferred since they yields a higher bit rate. Hence, on Figure 3 the attention should be focused on the 8k/64-QAM results. Even if the performance of one-antenna system with ICI cancellation are much better than no-ICI-cancellation schemes, still for the interesting 2/3 code rate the maximum speed falls below the 100 km/h. Only by using the combination of ICI cancellation and two antenna higher speeds are reachable.

The reason of the degraded performance at code rate 2/3 is due to the errors that are fed back into the ICI cancellation, starting from the first estimate of the data. In order to increase the reliability, the ICI cancellation has been performed iteratively, as described in the previous Section. Table 1 shows the maximum speed for two code rates and various number of iterations. The maximum speed range is related to the carrier frequency that is used. From the table we see that by using two or more iterations the performance significantly improves.

COMPLEXITY CONSIDERATIONS

One of the main purposes of this research was the implementation of the ICI cancellation scheme and channel estimation with an affordable complexity. The algorithm proposed by the authors in (4) was exceedingly complex and not suited for DVB-T standard, where no training symbol is present. With the new channel estimation scheme proposed in this paper, a strong reduction of complexity could be achieved. In the complexity comparison we considered both the storage and the circuitry needed for the computation. As measure unit we considered the area needed for to compute one 8K FFT.

The complexity comparison results among various techniques for mobile DVB-T are shown in Table 2. We considered the following systems:

- *Standard DVB-T receiver*. Channel estimator: time interpolation (2 pilots), frequency interpolation (8 pilots).
- *2 ant. with adv. ch. est.,* see Espineira R. and E. Stare E. (1). In this case two antenna are used and no ICI cancellation is considered. The signals from the two antennas are MRC combined before decoding. Time interpolation (12 pilots), frequency interpolation (16 pilots)
- *2 ant*. Similar to *2 ant. adv. ch. est.*, but with less complex channel estimators.
- *ICI canc. (1/2 ant.)*. The scheme described in this paper. With 1 or 2 antennas.

For each method we considered:

- The number of antennas required.
- The maximum speed that can be reached with each method with 64QAM and code rate 1/2.
- The FFT-equivalent required silicon area.

From Table 2 we observe that the systems with low complexity (up to 20 FFT silicon areas) do not guarantee the appropriate QoS for speeds above 60 km/h. Therefore they are not suitable for the reception of the DVB-T signal on motorways outside the city centre. In order to achieve higher speeds, ICI cancellation schemes or multiple antennas receiver should be considered. In the combination of multiple antennas and advanced channel estimation the main contribution to the silicon area is due to the extra storage needed for the longer time interpolation. On the other hand, for the ICI cancellation scheme the complexity is mainly due to the extra signal processing of the channel estimation and the ICI generation. The combination of ICI cancellation and receive diversity requires some more signal processing for the MRC but it merges the advantages of the two architectures.

CONCLUSIONS

A new signal processing architecture, based on the ICI cancellation principle, has been proposed for mobile DVB-T reception. The system allows the channel estimation as well as the ICI cancellation at an affordable complexity. Simulations have been carried out to evaluate the performance of the system with various transmitter configurations. As a result, the scheme uses one antenna and one front-end, while allowing speeds over 100 km/h, with a required silicon area similar to previously proposed two-antennas architectures. A combination of high mobility speed and high bit rate can be achieved by combining the ICI cancellation scheme with two or more antennas at the receiver.

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