On the exploitation of ACK Cancellation for Spatial Reuse in Unplanned Multi-hop WLANs

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Abstract— **Spatial reuse is an important challenge in multi-cell WLAN networks, such as Ad-Hoc and Mesh Networks, as well as sectorized antenna WLANs. However, the asynchronous handshake employed in the 802.11 MAC protocol is a severe limiting factor. Multiple parallel communications occurring between transmit/receive node pairs separated by a sufficient distance may be suddenly impaired by the asynchronous change of direction in the transmission occurring when a node replies with an ACK frame (this phenomenon, duly discussed in this paper, will be hereafter referred to as Hidden ACK Phenomenon). Goal of this paper is to show that Interference Cancellation mechanisms implemented as PHY-layer enhancements on the receiver side provide the ability to improve reception of frames interfering with bursty ACK transmissions in the proximity of the receiver. This improvement is achieved without requiring changes to the legacy MAC IEEE 802.11 basic access mode. Quantitative results are obtained for the widespread 802.11g PHY, taking into account its modulation and coding details. We quantify the Signal-To-Interference ratio under which ACK interference cancellation is effective, and derive the corresponding distance region where ACK cancellation is achievable. We conclude the paper by discussing the system-level applicability of our findings, with particular reference to the topological analysis to overcome the Hidden ACK Phenomenon through Interference Cancellation.**

I. Introduction

Recently, IEEE 802.11 [1] WLAN network architectures have evolved well beyond the traditional single-cell coverage paradigm. On one side, multi-hop wireless infrastructure networks, called 802.11 WLAN Mesh ([2], [3]), are under standardization in the 802.11 Task Group s [4], and are being considered as a low-cost solution for extending the WLAN coverage areas. On the other side, Access Points equipped by directional/sectored antennas [5] are a mean to dramatically improve the network capacity, by allowing multiple users, placed in different antenna beams, to simultaneously communicate with a same Access Point.

A fundamental required feature of multi-cell/multi-hop network architectures is the ability to provide spatial reuse, by exploiting simultaneous communication among pairs of terminals. For example, in a sectorized antenna scenario, stations in different beams may simultaneously exchange data with the AP, since interference across beams is canceled by appropriate beamforming techniques at the AP antennas. In a multi-hop wireless network scenario, protection from interference is instead guaranteed by the terrestrial distance between the network nodes. Previous works have in fact demonstrated that multiple communications using the same channel in a multi-hop network may happen simultaneously at different location without interfering each other under the condition that the concurrent pair of Mesh APs are separated by a given spatial distance, that is with high network sizes, see e.g. [6]. This scenario may be not very effective in small scale unplanned Mesh Network where the required separation distance could be too high [7].

It has been proven that, due to its asynchronous MAC operation, the 802.11 technology is poorly performing in the above considered scenarios. In fact, the Distributed Coordination Function (DCF), namely the MAC protocol employed by IEEE 802.11, suffers from various problems, such as hidden/exposed nodes, which severely impairs its possibility to effectively exploit spatial reuse. Of specific interest in this paper is the effect of a reply ACK, transmitted in response to a data frame. As shown in section II, even if the hidden/exposed terminal problem is solved for two or more pairs of transmitting stations, this is not in general the case when, in one of these communication pairs, inversion of the transmission direction occurs, as it always happens when a station replies with an ACK. In what follows, we'll refer to "Hidden ACK Phenomenon" the case in which an ACK generated in response to a successfully delivered frame results into the disruption of a simultaneously ongoing communication by another pair of nodes.

Improvements of the 802.11 MAC, such as the

RTS/CTS operation, may be considered to mitigate the impact not only of the well known Hidden terminal phenomenon, but also of the Hidden ACK Phenomenon. However, the RTS/CTS effectiveness is largely debated. First, its overhead is particularly critical [8], [9], especially when link rates are scaled up to the 54 mbps 802.11a/g speeds. Moreover, its usage in a multi-hop network results into a very low spatial reuse effectiveness [10], [11].

Goal of this paper is to mitigate the Hidden ACK Phenomenon by adopting very simple multi-user detection techniques, deployable over the legacy 802.11 PHY. Specifically, we propose to employ Successive Interference Cancellation (SIC) mechanisms [12] in the receiver baseband. As shown in what follows, this can be done with negligible impact on the 802.11 receiver implementation. Due to its emerging importance, this paper focuses on the widespread 802.11g PHY [13].

We take advantage of the fact that an ACK frame acts as a short burst of interference. Moreover, we rely on the property that an ACK frame is transmitted at basic rate, and thus easily decoded (and thus used to feed the data chain of the SIC receiver) even in the presence of small signal to noise ratio. In the rest of this contribution, we specifically focus our quantitative assessment to a Multi-Hop / Mesh Network scenario.

The paper is structured as follows. Section II describes the Hidden ACK Phenomenon. Section III reviews the basic operation of a Successive Interference Cancellation mechanism and provides insights for its application to Hidden ACK Phenomenon in 802.11g Mesh Networks. Section IV describes the related simulation model and section V reports numerical results and assesses the spatial region where ACK Interference Cancellation can be successfully applied.

II. Hidden ACK Phenomenon

The Hidden ACK phenomenon is a particular case of the well known Hidden terminal phenomenon. It occurs when two transmitting nodes are sufficiently separated in order not to raise an hidden terminal problem (i.e. their transmissions are both successful), but the expected receivers are close and an hidden terminal phenomenon occurs when one of the two communicating pairs asynchronously switches transmission direction when replying with an ACK.

This problem is illustrated in figure 1. In the figure, terminals T_1 and T_2 are outside their carrier sense region (not depicted in the figure). Hence, following the CSMA/CA rules, they may be given the chance to

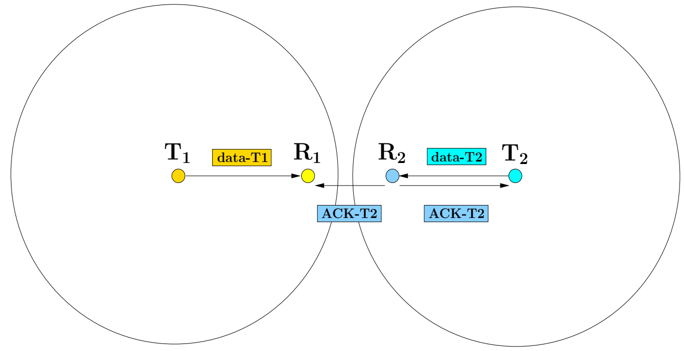

Fig. 1. Hidden ACK Phenomenon: the ACK transmitted from R_2 to T_2 interferes with the transmission from T_1 to R_1

transmit in parallel to their intended receivers (in the figure, R_1 and R_2, respectively). We further assume that the transmitting node T_2 is not an hidden terminal for the $T_1 \rightarrow R_1$ communication, i.e. T_2 interference region does not reach R_1. We also assume that a similar hyphotesis hold for the $T_2 \rightarrow R_2$ communication. In these conditions, a successful transmission $T_1 \rightarrow R_1$ can occur simultaneously with a a successful $T_2 \rightarrow R_2$ transmission.

This would clearly operate under the assumption that the transmission is unidirectional. Unfortunately, the 802.11 handshake imposes an half-duplex process where an ACK is always sent by the receiver upon the successful reception of an unicast frame (*basic access mode*). Since the frame-ACK exchange is asynchronous, one of the two considered receivers, say terminal R_2, will starts replying with an ACK while the parallel transmission of a data frame from T_1 to R_1 is still in progress. Hence, reception of terminal R_1 is impaired by the fact that the ACK transmitted by R_2 overlaps with the data frame transmitted by T_1, thus possibly causing reception failure. This problem, in this paper referred to as "Hidden ACK Phenomenon" is shown to occur not only in multi-hop scenarios, but also (and perhaps even to a greater extent) in a sectorized antenna scenario (see e.g. [5], which refers to this phenomenon with the name "ACK Suicide").

Note that this issue is inherent in the asynchronous operation of the 802.11 MAC protocol: of course the "obvious" solution of redesigning a brand new synchronous MAC for 802.11 is not viable! Although it is current option in the research community involved in mesh networks that a MAC redesign for a mesh environment would be extremely helpful, and the IEEE 802.11s Task Group [4], in its first initiatives, is not only considering enhancements in the traditional 802.11 Dis-

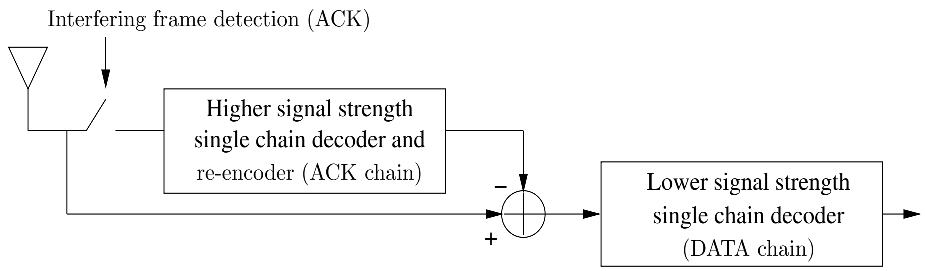

Fig. 2. Interference cancellation: the SIC Receiver in IEEE 802.11

tributed Coordination Function, but it is also evaluating more radical changes in the 802.11 MAC protocol in the design of a new Mesh Coordination Function capable of providing effective spatial reuse.

III. Successive Interference Cancellation for Hidden ACKs

We propose to mitigate the above mentioned problem by employing a Successive Interference Cancellation (SIC) receiver [12], a technique effectively employed for multi user detection [14], [15]. Introduction of SIC in 802.11 may be applied to current IEEE 802.11 PHY standards. SIC is especially viable in a Mesh Network context since, unlike in ad hoc networks, relay nodes are owned and managed by the infrastructure provider, and thus may be easily upgraded with advanced hardware, and only at the receiver side of the baseband.

The basic SIC operation is outlined in figure 2. The SIC receiver is composed of two independent *chains*, one for treating the signal generated by the reception of the data frame (hereafter referred in short as DATA signal), and the second for processing the burst interference induced by an hidden ACK (hereafter referred to as ACK signal). This second chain is capable of: i) detecting that an ACK frame is being interfering with a DATA frame in reception, ii) properly decoding the ACK signal, iii) re-encoding and filtering the ACK signal. Finally the ACK signal is iv) subtracted from the received signal, and v) the resulting DATA signal is decoded through a separate chain. In what follows additional details are provided.

The condition under which an ACK frame is properly decoded is of great importance (indeed, its quantification is an explicit target of this paper). Since, in the ACK chain, the signal to be decoded is the ACK signal, while the DATA signal acts as interference, correct ACK decoding depends on the signal-to-interference ratio:

$$SINR = \frac{ACK\ RSSI}{(DATA\ RSSI) + NOISE}, \qquad (1)$$

where the ACK and DATA RSSI (received signal strength indicator) are respectively the DATA and ACK received power, and NOISE is the thermal noise at the receiver. Moreover, a further condition to enable the ACK chain is that the PLCP ACK preamble does not overlap with the PLCP DATA preamble, since otherwise synchronization and channel estimation would be dramatically impaired. Indeed, this is not a critical problem in 802.11g as the PLCP lasts 16 μs (much shorter than a typical DATA frame side which lasts several hundreds of μs depending on its payload size and on the employed rate) and thus the probability that the two PLCP preamble overlap is marginal.

Upon successful ACK signal decoding (valid Frame Check Sequence in the ACK frame), the ACK frame is re-encoded, filtered with the estimated wireless channel impulse response, and subtracted from the aggregate received signal. Note that, assuming ideal channel estimation, the DATA chain is fed by an interference-free DATA signal, as only thermal noise is left.

We finally remark that practical implementation of a dual chain may take advantage of the fact that the IEEE 802.11 standard allows only half duplex operation. Hence, the encoder chain of the baseband, which is not used for transmission while receiving, may be employed to re-encode the ACK signal.

IV. System Model of the Simulator

Link level results has been achieved using a detailed 802.11g baseband simulator we have developed in Matlab. Our simulator implements all the modules highlighted in figure 3, which shows the legacy 802.11g encoder and (single-chain) decoder, and properly combines these modules in the SIC received architecture previously shown in figure 2. Details are provided in the following subsections.

A. Transmitter: IEEE 802.11g

We use the legacy IEEE 802.11g bit-punctured coding scheme based on 64-state rate-1/2 convolutional code.

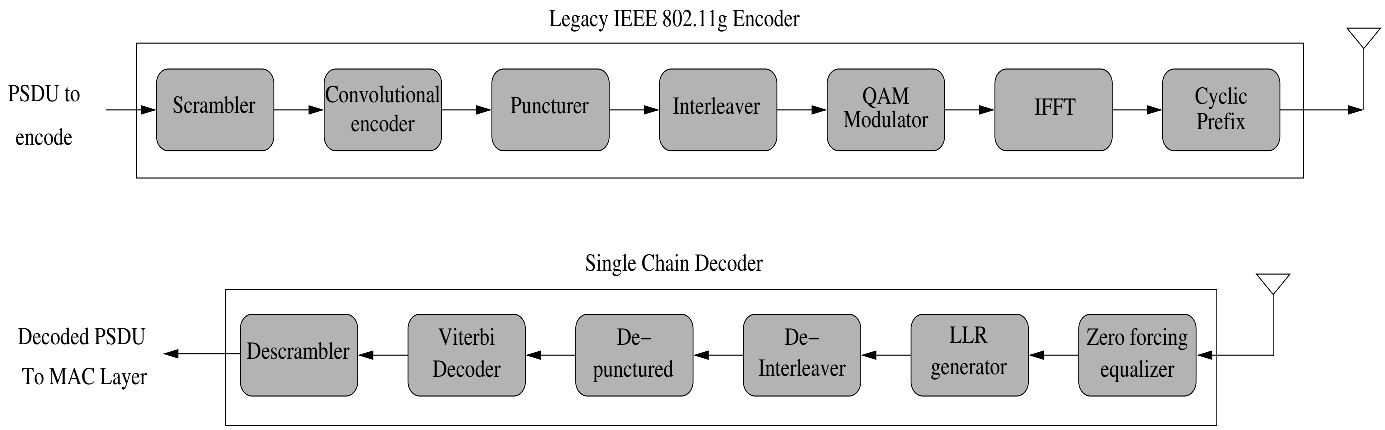

Fig. 3. IEEE 802.11g encoder and single chain decoder of a legacy terminal

The OFDM-PHY parameters, including the number of sub-carriers, are taken from the IEEE 802.11g standard. Each terminal is equipped with one omni-directional antenna with 5 dBi gain. The EIRP transmitted power is set to 20 dBm, to comply with the European regulation.

The DATA signals have been modulated and coded for various 802.11g rates (6, 12, 24, 36 and 54 mbps). Following the specification of the standard, the ACK signals were transmitted at basic rate, i.e. 6 mbps for IEEE 802.11g.

B. Channel

We assume a block fading model in which the channel remains constant over the multiple OFDM symbols that compose an OFDM packet (this model being suitable for static or slowly moving terminals, which is the case for a Mesh Network). We have consider as model a FIR filter (i.e. a tapped delay line model), which composes the channel impulse response of complex taps using Rayleigh distributed magnitude and random uniformly distributed phase. The taps are variables with an exponentially decaying power delay profile characterized by a 75 nanosec root mean square (RMS) delay spread.

The average received power at each terminal is

$$P_r = K_0(d_k/d_0)^{-\beta}P_t$$

where d_0=1m is a reference distance and d_k is the wireless link distance, P_t=20 dBm is the EIRP transmitted power, and

$$K_0 = (c/4\pi d_0 f_c)^2 = 9.89 * 10^{-5}$$

is the channel power gain (W) at the reference distance (being f_c=2.4 GHz and $c = 3 * 10^8$m/s the speed of light).

To model a Mesh outdoor pico-cell in the f_c=2.4 GHz band, the path loss has been set to $\beta = 3.3$ and the shadowing standard deviation is σ_{SH}=$5.9dB$ (these values being derived from experimental results [16]). Table I summarizes the main channel parameters.

C. Receiver: SIC decoder

We suppose that the ACK signal arrives randomly within the DATA signal and perfect ACK and DATA timing synchronization is performed in the SIC. The SIC receiver is made up of two decoder chains, while a legacy receiver has just one decoder chain (compare figure 2 and 3). Particularly, we use the soft Viterbi decoder for bit-level decoding of both DATA and ACK frame chain of the SIC receiver and assume perfect channel knowledge. Soft bit detection adds a certain degree of complexity to the receiver, but its performance benefit over hard detection makes this added complexity worthwhile. We point out that the thermal noise temperature is 295 Kelvin degrees and the noise figure is 5 dB, giving a noise strength of -95 dBm.

V. Performance Evaluation and topological interpretation of the results

Following the recommendation of the standard [13], numerical results have been obtained considering data frames of size 1000 bytes (more formally, PSDU inclusive of the MAC header and of the FCS and trailer bits),

Path loss β	Shadowing σ_{SH}	RMS delay spread
3.3	5.9 dB	75 ns

TABLE I

MAIN WIRELESS CHANNEL PARAMETERS

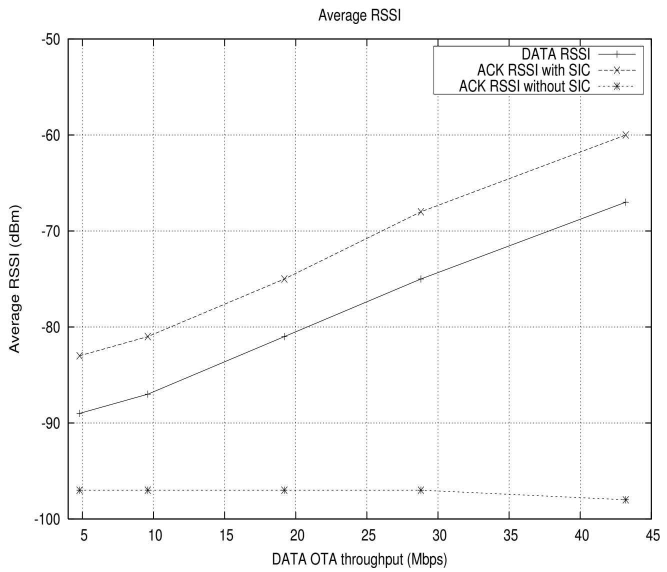

Fig. 4. Average DATA/ACK frame RSSI vs DATA over-the-air throughput

transmitted at various 802.11g rates, and interfering with an ACK frame transmitted at basic 6 mbps rate.

As performance figure, we have derived the receiver sensitivity required to reach a target frame error ratio (FER) at each fixed rate. Receiver sensitivity is the weakest RSSIs pair (DATA RSSI,ACK RSSI) at which the receiver can successfully decode both DATA and ACK frames at the target FER. Because RSSI varies due to shadowing effects, figure 4 displays the average RSSI over the link, and reports it in dBm levels.

In the absence of ACK bursty interference, we have first computed the average RSSI for DATA frames necessary to meet a FER of 10% (according to the standard [13], the physical layer analysis should be operated with such a target FER=10%). On top of this, we have then accounted for the further degradation induced by the bursty interference caused by hidden ACKs. Specifically, we computed the ACK RSSI value such that the overall resulting DATA frame FER increases up to 20%, for both the cases of SIC receiver and legacy receiver. These results are reported in figure 4. In the x-axis, we report the over-the-air (OTA) throughput, defined as the amount of DATA that can be transmitted without error (MAC level retransmissions of course not being accounted). The OTA throughput can be expressed as $R(1-FER)$ where R is the data rate employed for the DATA frame, and FER is set to 20% as a consequence of the above discussion.

First, the figure shows that, as obvious, the average DATA RSSI necessary in order to achieve a given FER target increases with the data rate. Much more interesting is the quantification of the ACK RSSI necessary in order to enable ACK cancellation with an overall resulting FER target of 20% (i.e. the ACK contributes to the DATA frame FER with an extra 10%). The figure shows that the difference between the ACK RSSI and the DATA RSSI is virtually constant over the various considered rates, and amounts to about

$$SINR = 6 \div 7 \ dB \qquad (2)$$

This value quantifies the SINR target necessary to enable ACK cancellation (see equation 1 ion section III, and the related discussion).

Finally, for comparison, the figure 4 reports the ACK RSSI under which a DATA frame FER of 20% is obtained without the usage of the ACK chain. This value if of course the same regardless of the received used as an ACK whose RSSI is lower that the DATA RSSI cannot be successfully decoded and, in turns, canceled.

Figure 4 allows to draw an important consideration. It shows that there are three possible operative regions:

- *ACK cancellation region*, which occurs when the ACK RSSI is greater than the minimum level that allows its detection, decoding and successive cancellation (curve ACK RSSI with SIC in figure 4);
- *No interference region*, which occurs when the ACK RSSI is lower than the threshold under which its effect of the DATA frame is negligible (curve ACK RSSI witout SIC); and
- *Single transmission region*, which is the region where the ACK interference results in disturbance and no cancellation is technically possible due to the too limited ACK RSSI value.

A. Topological interpretation

It is very effective to map these regions in geometric terms, i.e. refer to mutual node distance rather than ACK/DATA RSSI values. This geometric mapping is reported in figure 5. Quite interestingly, this figure shows that an approximately linear relationship exists between the communication distance d between the DATA frame transmitted and the intended DATA receiver, and the interference distance D between the ACK frame transmitter and the DATA receiver.

Let $\alpha = d/D$ be the ratio between these distances. The previous analysis has clearly demonstrated that α is a value greater than 1, since the ACK RSSI must be greater than the DATA RSSI. Numerical results presented in figure 5 seems to suggest that a reasonable approximation is $\alpha = 1.4$.

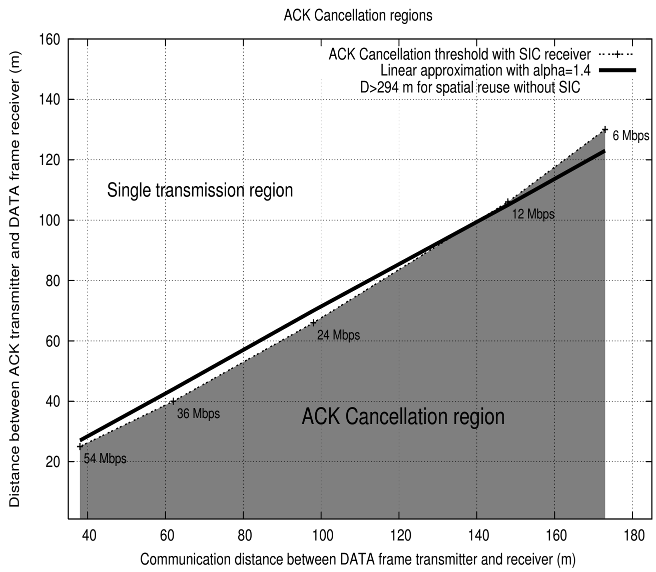

Fig. 5. Link distance for ACK cancellation in IEEE 802.11g mesh networks

Figure 6 shows an illustrative example. The transmitter T_1 is sending a DATA frame to a receiver R_1 in its carrier sense range. The condition under which a terminal R_2 may transmit an ACK interfering frame (to an arbitrary destination T_2), which will be subsequently canceled by the receiver R_1, is that, as stated above, the distance $d(T_1, R_1)$ must be greater or equal than α times the distance $D(R_2, R_1)$.

Let now x be the distance between T_1 and R_2. It is straightforward to derive that this condition holds whenever the receiver R_1 is placed in the intersection of the communication region range of T_1 and a circle centered in a point aligned with T_1 and R_2, and at distance $C = \alpha^2/(\alpha^2 - 1)x$ with respect to T_1, and with radius $r = \alpha/(\alpha^2 - 1)x$. Figure 6 graphically illustrates this situation for the case $\alpha = 1.4$: in such case the center of the circle is, approximately, at distance $2x$ while its radius is $r = 1.4x$. This figure shows that the region in which the ACK cancellation can be exploited is not marginal, despite the fact that the SINR value reported in equation 2 is fairly high. A thorough assessment of the effectiveness of the ACK cancellation approach in terms of high level system performance would require a detailed network simulator model which is way out of the goals of this present paper (and is object of current ongoing work). We remark that ACK cancellation comes with no performance drawbacks, i.e. any advantage it provides is only traded off by a slightly increase in the received cost and not by a performance degradation in normal operation conditions.

VI. Conclusion

To the authors knowledge, this paper is the first that aims at quantify the impact of interference cancellation in an 802.11(g) multi-hop scenario. Specifically we envision interference cancellation as a viable approach to reduce the impact of short bursty interference caused by the asynchronous nature of the 802.11 MAC (the Hidden ACK phenomenon).

Through link level simulation, and with reference to the widespread 802.11g physical layer, we have identified the quantitative conditions under which ACK cancellation is possible by employing a successive interference cancellation receiver. This receiver is perfectly compatible with the rest of the 802.11 protocol stack (i.e. it does not affect neither the PHY nor the MAC operation), and thus it can be integrated in off-the-shelf devices.

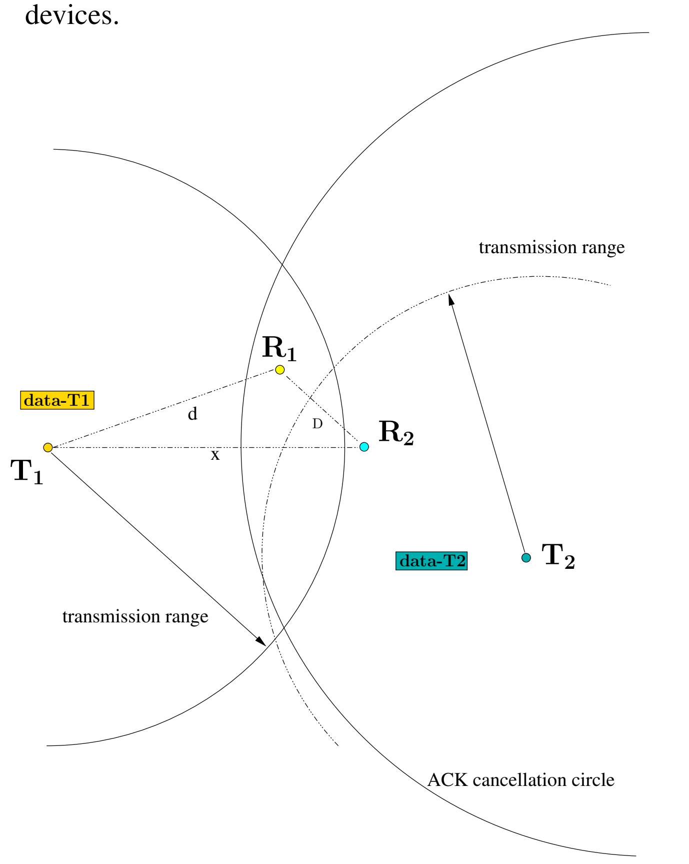

Fig. 6. Topology analysis for the spatial reuse with ACK interference cancellation

Our numerical results demostrate that, despite the resulting fairly large difference between the ACK and DATA frame RSSI values, there is a non negligible spatial region in which ACK cancellation is successful. Our results are also very interesting in perspective terms. In fact, we are planning to address the same issue in the frame of the emerging 802.11n physical layer [17], [18]. Given the 802.11n proposed enhancements at the transmitter side, which allows for two or more uncorrelated antennas and advanced coding scheme such as Low Density Parity Check codes, we intuitively expect to achieve a larger ACK cancellation region, i.e., with reference to the symbology introduced in section V, a significant smaller α parameter, and hence an increased spatial reuse.

ACKNOWLEDGMENTS

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