Cross-Layer Error Control Optimization in WiMAX

Dzmitry Kliazovich*, Tommaso Beniero+, Sergio Dalsass*, Federico Serrelli+, Simone Redana§, and Fabrizio Granelli*

* DISI – University of Trento
Sommarive 14, I-38050, Trento, Italy
Email: [kliazovich, granelli]@disi.unitn.it

+ DEI – Politecnico di Milano
Piazza Leonardo da Vinci 32, I-20129, Milano, Italy
Email: [beniero, serrelli]@elet.polimi.it

§ Nokia Siemens Networks S.p.A.
Monfalcone 1, I-20092, Cinisello Balsamo, Italy
Email: Simone.Redana@nsn.com

Abstract—**WiMAX is one of the most promising emerging broadband wireless technologies. As a consequence, data transfer performance optimization represents a crucial issue due to TCP limitations in wireless environment. In this study, we focus on the overhead deriving from the multilayer ARQ employed at the link and transport layers. To the aim of reducing unnecessary burden on the wireless link, we propose a cross-layer ARQ approach, called ARQ Proxy, which substitutes the transmission of TCP ACK packet with a short MAC layer request on the radio link. Packet identification is achieved through the use of hash functions applied to the packet headers. Performance of the ARQ Proxy is evaluated using an IEEE 802.16e system level simulator which includes realistic physical layer implementation. The results demonstrate good agreement with the design objectives and achieve the expected levels of system capacity increase, reduction of round trip time, and higher error rate tolerance.**

Keywords-WiMAX, ARQ, HARQ, cross-layer, ARQ proxy

I. INTRODUCTION

Nowadays, wireless networks are becoming ever more widely deployed and used to access services over the Internet, thus rising novel issues and challenges. Indeed, the performance of TCP/IP protocols suite has been reported to be much lower in wireless networks than in fixed networks [1]. In particular, the Transmission Control Protocol (TCP) experiences heavy performance degradations over wireless networks due to non-congestion related packet losses and varying Round Trip Times (RTT).

One of the leading technologies for wireless data communications with metropolitan coverage capability is the Worldwide Interoperability for Microwave Access (WiMAX) [2]. In order to counteract wireless channel limitations such as fading, signal interference, limited bandwidth and available transmission power, WiMAX, like most of other wireless technologies, employs error protection techniques implemented at the physical and the link layers. By using them it becomes possible to compensate the link error rate by several orders of magnitude bringing it from $10^{-1} – 10^{-3}$ [3] to $10^{-5} – 10^{-7}$ [4]. The achieved error rates become acceptable by the most widely used protocol reference model TCP/IP, originally designed for low error rate wired networks.

However, WiMAX error correction strategies lead to an increased overhead on the wireless link, required for transmission of acknowledgement information, while reliability and congestion control mechanisms implemented by TCP are based on a different error recovery technique, implemented at the transport layer.

In this paper, following a detailed analysis of retransmission and error recovery techniques implemented at the WiMAX physical and link layers as well as at the transport layer by TCP, we identify an area for performance optimization by introducing multilayer awareness and cooperation in the error recovery process.

This approach, which can also be referred as cross-layer optimization of multilayer error control in WiMAX networks, was already introduced for UMTS and WiFi networks in [5] and [6] respectively. However, the main contribution of this paper corresponds to its adaptation to the WiMAX environment. In particular, in this paper we take the advantages of the WiMAX-specific coding, employed at the physical layer by the error recovery, which is extended to carry information required by the ARQ proxy approach.

The rest of the paper is organized as follows: Section II presents the details on error recovery techniques implemented in WiMAX; Section III presents the proposed optimization approach; performance evaluation results are provided in Section IV, while Section V draws some conclusions as well as discusses the directions for future research on the topic.

II. MULTI-LAYER ARQ IN WIMAX

Error recovery technologies employed by WiMAX are classified into Automatic Repeat reQuest (ARQ) and Hybrid ARQ (HARQ).

The ARQ technique implemented at the link layer can operate on link layer data units on cumulative or selective basis, or on a combination of the above. According to this scheme, the receiver checks the integrity of a block of link layer data units and reports the result back to the sender by using a standalone or encapsulated acknowledgment in an outgoing data frame message.

HARQ, implemented through a PHY-MAC cross layer mechanism in WiMAX, is a combination of Forward Error Correction (FEC) with retransmission techniques. HARQ implementation is organized according to a multichannel stop-and-wait approach where the sender should wait for the receiver feedback for every packet sent at the physical layer on any particular HARQ channel.

Fig. 1 illustrates a single TCP DATA packet delivered from the content provider located in the fixed part of the network to the Mobile WiMAX Station (MS). The Base Station (BS), after

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reception of a TCP data packet from the fixed network (File Server), forwards it over the radio link to the appropriate MS. This downlink transmission includes also heavy physical and link layer overhead. In case of successful reception, the MS sends an HARQ ACK response to the BS and forwards the received TCP data packet up to the TCP layer of the protocol stack. Consequently, the TCP layer generates a TCP ACK. This one represents ordinary payload for the WiMAX link layer: before it can be transmitted on the wireless link, uplink resources should be requested and a corresponding assignment grant should be received at the MAC layer. Moreover, TCP ACK transmission requires an HARQ ACK from the BS.

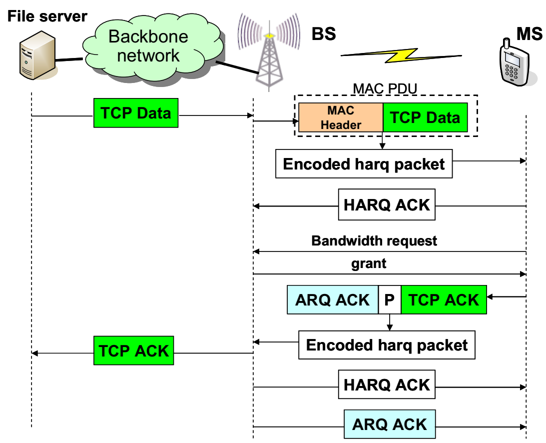

Figure 1. TCP packet delivery in a WiMAX network.

Summarizing, a single transport-layer data transmission is acknowledged three times: once at the transport layer and two times at lower layers. Moreover, while HARQ feedback is relatively small (just of several bits), the TCP ACK along with the headers added at the network, link and physical layers consumes large amount of network resources.

In case ARQ and HARQ are enabled on a MAC connection carrying a TCP flow, multilayer error recovery at the MAC and transport layers takes place. Although this increases reliability in the wireless environment, the ARQ acknowledgement feedback consumes a significant amount of radio resources. More precisely:

- A standalone TCP ACK requires at least 46 bytes (20 for TCP, 20 for IP, 6 for MAC headers). If ARQ is enabled, there are another 4 bytes for the ARQ CRC. Instead, a piggybacked TCP ACK entails no overhead since ACK information is provided inside TCP header.
- An UL HARQ acknowledgement occupies half a considerable portion of the uplink slot, while a downlink HARQ ACK is only one bit placed in the downlink HARQ ACK IE contained in the DL-MAP message.
- The size of an ARQ acknowledgement depends on the acknowledgement scheme employed and is quite variable. However its minimum value is 4 bytes.

For underlining this aspect, Fig. 1 shows the transmission, reception and acknowledgement of a TCP (+IP) data packet in a WiMAX network when both ARQ and HARQ are enabled. In such scenario, a single TCP data packet is acknowledged five times: one at the transport layer and four at MAC layer. As a consequence, this multilayer error recovery consumes a significant amount of resources, especially in the uplink direction.

III. ARQ PROXY FOR WIMAX

A. Overview

ARQ proxy approach enables cooperation between error recovery mechanisms implemented at different layers of the protocol stack, with the purpose of reducing the acknowledgement overhead transmitted over the wireless channel and hence to increase the wireless network capacity.

More specifically, for every data packet sent to the MS the BS prepares a standalone TCP ACK packet acknowledging its successful reception and stores it in the memory. TCP ACK generation at the base station is implemented through a simple copy of the appropriate fields of IP and TCP headers from the forwarder TCP data packet into a previously allocated TCP ACK template in memory.

At the receiver side, in case the received TCP data packet triggers TCP ACK generation, the MS tries to substitute its transmission with a short request sent at the link layer. As soon as this substitution request reaches the BS, the corresponding TCP ACK is selected from the memory and issued into the backbone network.

This substitution request is composed of TCP data packet identifier (id) for which the triggered TCP ACK was generated. Such id is obtained by applying a hash function onto the TCP data packet headers. The use of hash functions allows the BS and MS to compute the TCP ACK id independently without the need for direct communication.

The main benefit of using ARQ proxy approach lies in the network capacity improvement deriving from the difference between the amount of bandwidth resources (bandwidth and delay) required for TCP ACK transmission in the wireless channel and network resources associated with the short message for delivery request.

The fact that all TCP ACKs generated at the BS and sent into the network core are requested by the receiver node allows the proposed method to maintain end-to-end semantics. The absence of TCP ACK in the radio channel leads to sustaining higher error rates, while the reduced RTT of the connection leads to TCP performance increase due to the faster feedback.

It is also important to note that ARQ proxy does not require maintenance of any TCP state related information at the BS which favours its incremental deployment and application in a variety of mobility scenarios.

B. ARQ Proxy Implementation using WiMAX HARQ

The crucial point of ARQ proxy adaptation to the WiMAX scenario lies in finding a way for feedback delivery from the MS to the BS able to carry the TCP ACK identification (afterwards referenced as TCP ACK ID).

Following the analysis of the error recovery schemes implemented by the IEEE 802.16 standard, the Hybrid ARQ (HARQ) positioned at the physical/link layers appears to be suitable for this task, as it follows a multichannel stop-and-wait approach which specifies the sender to wait for positive or negative feedback from the receiver before proceeding with subsequent frame transmission.

HARQ information is transmitted by the MS in the appropriate HARQ ACK region where only the uplink PUSC permutation scheme is allowed. According to IEEE 802.16 standard, with this permutation scheme an OFDMA slot is made up of six tiles. The even tiles (Tile0, Tile2, and Tile4) are used for one HARQ ACK and the odd tiles (Tile1, Tile3, and Tile5) are used for another HARQ ACK that can belong to a different MS.

In WiMAX, the importance of HARQ information is high since its incorrect reception could cause the loss and further retransmission of a large amount of data. For this reason, HARQ ACK region it protected with the most robust modulation scheme (QPSK). Moreover, instead of Forward Error Correction (FEC), the proprietary error protection scheme is designed for HARQ ACK channel with the purpose to provide high redundancy. Specifically, the HARQ ACK and NACK are encoded with a 3-symbol codeword where each symbol ranges between '0' and '7' (Tab. 1).

Table 1. HARQ acknowledgement coding.

HARQ - acknowledgement	Codeword
ACK	0.0.0
NACK	4.7.2

For each of the eight symbols, the IEEE 802.16 standard defines the exact modulation pattern to use in the tile where it is carried, i.e. which QPSK symbol has to be transmitted on each subcarrier of the tile. Therefore, error protection of the HARQ acknowledgements is given by two contributions:

1. The redundancy at level of modulation patterns: only 8 modulation patterns are used although 65536 (4^8) of them are available within a tile.
2. The redundancy at level of code-words: there are 512 (8^3) codeword available, but from this set only two codewords (0.0.0 for ACK and 4.7.2 for NACK) are used.

In order to enable HARQ acknowledgments to carry additional information required by ARQ proxy approach, additional combinations of codewords may be used at the expense of reduced redundancy in HARQ error protection.

Since each tile contains one symbol among eight, it can carry three bits only and since a HARQ ACK region consists in three tiles, this last one can contain only nine bits.

Therefore, a HARQ acknowledgement cannot directly carry a TCP ACK ID employed by ARQ proxy scheme, which is usually larger than nine bits in size. However, additional codewords can be utilized to carry uplink bandwidth reservation requests. In fact, assuming fixed size for the TCP ACK ID, the MS can simply specify the number of TCP ACK IDs it wishes to transmit including it into the HARQ acknowledgement. This can be accomplished using a subset of the 512 codewords and by associating to each codeword of the subset a specific number of TCP ACK IDs that the MS has to transmit. However, by increasing the number of used codewords, the HARQ ACK error rate, or more generally the codeword error rate (CWER), can increase and therefore the set of used codeword should remain relatively small.

The number of new codewords to introduce depends on the number of TCP data packets transmitted in the downlink HARQ packet. Since TCP packets usually have a big size and this corresponds to the most common Ethernet MTU equal to 1500 bytes, it is unlikely to have more than eight TCP packets in a single downlink frame. Therefore it seems reasonable to extend the number of used codewords in order to permit to a MS to require the bandwidth resources needed for the transmission of eight TCP ACK ID values. This choice does not sensibly affect the HARQ ACK error rate if the new codewords are chosen so that to maximize the Euclidean distance between the used codewords.

C. *ARQ Proxy Implementation using WiMAX ARQ*

The use of HARQ feedback for ARQ proxy implementation presented in the previous section is considered as default due to its simplicity and deterministic behavior. However, other possibilities of adapting ARQ proxy in the WiMAX scenario exist. One of them is related to the use of ARQ feedback scheme implemented at the link layer.

The ARQ operates on variable size data blocks. However, the fact that the size of the ARQ payload and the payload itself can be easily identified within the boundaries of MAC layer protocol data unit (MAC PDU) makes it possible to include additional ARQ proxy related information including TCP ACK IDs and corresponding uplink bandwidth requests.

A possible ARQ-based scheme enabling ARQ Proxy support is presented in Fig. 2 and makes use of the following elements:

- A fixed-length field to make bandwidth request. Through this field the MS informs the BS about the number of TCP ACK IDs it belongs to. For this task it is enough a 1 byte field which shall be inserted at the end of the ARQ payload, after the last ARQ feedback IE or TCP ACK ID, if it is present.
- TCP ACK IDs which are immediately inserted after the last ARQ feedback IE and before the TCP ACK ID bandwidth request field (if present).

Obviously in order that such scheme works the TCP ACK ID size must differ from the one of the TCP ACK ID bandwidth request field.

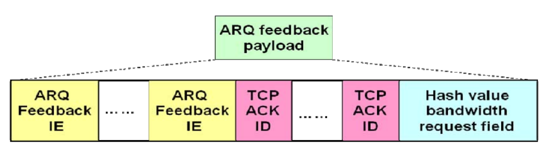

Figure 2. ARQ acknowledgement supporting ARQ Proxy

IV. Performance Evaluation

A. *Simulation Model*

In order to evaluate the performance of the proposed mechanisms we used a ns2-based [7] system-level simulator compliant to IEEE 802.16e standard, developed by NSN. used. The simulator implements the OFDMA PHY mode with TDD duplexing by using the frame parameters specified in the *MTG profile* [8].

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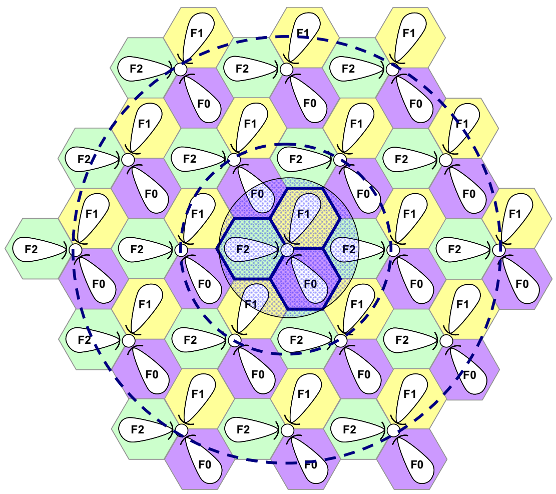

Figure 3. Simulated network topology

The simulated network, shown in Fig. 3, is a regular hexagonal cellular topology which includes a central trisectorial target site for statistics measurement and two additional interference rings, i.e. 19 independent sites in total. An intra-site frequency reuse-3 is used thus making available in each sector of a site 5MHz of bandwidth around the central frequency of 2.5GHz. In this scenario, a downlink TCP connection is established between the file server, located in the fixed network, and each of the 15 MSs placed in the traced cell of the simulated network.

The wireless channel is modeled by considering the SIEMENS *Ray-Tracing@* 2.5GHz model for the pathloss, a log-normal shadowing with 8dB of standard deviation and fast fading. The latter is simulated run-time by a trace previously produced through link level simulation of the SCME channel model developed in the context of the WINNER project [9].

The BS antenna (one for each sector) is modeled assuming a 65 deg (-3dB) with 50dB of front-to-back ratio pattern and it's characterized by a gain of 17.5dBi and a transmission power of 40dBm. MSs instead are supposed to be equipped with omnidirectional antennas. All system parameters are summarized in Table 2.

Table 2. System parameters.

Parameter	**Value**
Number of sites	19 (two interference rings)
Number of sectors per site	3
BS-BS distance	0.9 km
Center frequency	2.5 GHz
Reuse scheme	Reuse-3
Total channel bandwidth	15 MHz
Channel bandwidth per sector	5 MHz
NFFT	512
Frame duration	5 ms
BS PHY model	
BS Tx power/sector	40 dBm
BS antenna height	30 m
BS antenna pattern	65° (-3 dB), 50 dB front-to-back ratio
BS antenna gain	17.5 dBi
TS PHY model	
TS antenna height	1.5 m
TS antenna pattern	Omnidirectional
TS Noise Figure	7 dB
TS mobility	fixed

B. Simulation Results

Fig. 4 shows the total uplink ACK feedback measured during a 95-seconds simulation for both ARQ proxy enabled (ARQ Proxy ON) and ARQ proxy disabled (ARQ proxy OFF) cases. In this scenario the uplink traffic is mostly composed of acknowledgement feedback and bandwidth reservation requests.

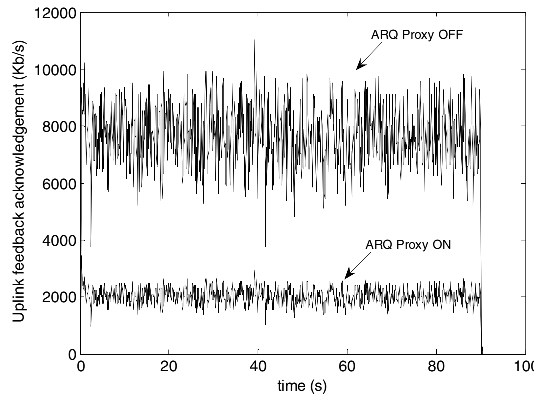

Figure 4. Uplink ACK feedback.

The results obtained by several simulations demonstrate that the ARQ Proxy optimization offers significant reduction of the uplink load due to optimization of error recovery procedures.

Numerically, the results correspond to the difference between the size of a standalone TCP ACK and its corresponding hash value which equals approximately 5.6 Kb/s.

In WiMAX, hash values are embedded within MAC PDUs, so that they may be protected by error recovery procedures. The smaller size of the hash values reduces exposure to the link errors if compared with large TCP ACK frames. As a result, fewer ACKs are getting lost which corresponds to a higher uplink capacity as well as an increased TCP flow performance.

This deduction is confirmed by simulation results obtained by employing only the ARQ as error protection technique in uplink. Fig. 5 shows the packet error rate (PER) of the ARQ acknowledgement packets sent by a MS, obtained by varying the uplink SLER (slot error rate) between 0 and 50%.

The network resources saved by the use of the ARQ Proxy can be used by the same MS or by other nodes operating in the same BS cell for transmitting further data.

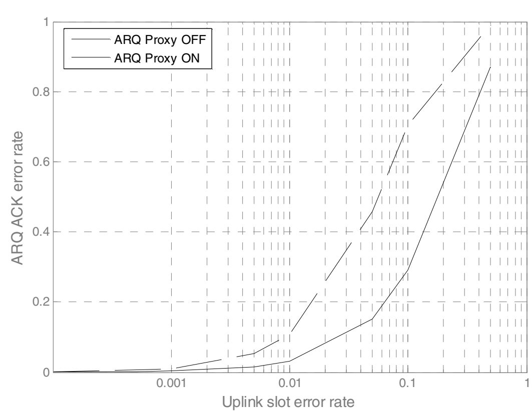

Figure 5. PER of ARQ acknowledgement packets sent by a MS.

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ARQ Proxy has also a significant impact on the RTT of the TCP connection. Fig. 6 reports the measured RTT for the downlink TCP connection established between the remote file server and a MS.

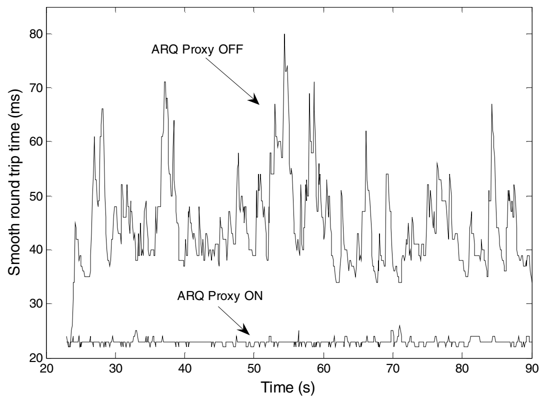

Figure 6. Round Trip Time (RTT) for a downlink TCP connection.

In a heterogeneous network, like WiMAX, the RTT comprehends the transmission delay both in the backbone network and in the wireless one. The ARQ Proxy approach reduces the time required for TCP ACK transmission over the wireless links from MSs by reducing its following components:

1. The uplink transmission errors and hence the retransmission of acknowledgements in uplink.
2. The time needed for making uplink bandwidth requests.

The latter point is justified by the fact that bandwidth requests made using ARQ or HARQ acknowledgements are faster than those made using conventional reservation. In fact, in case of an HARQ-based request, the transmission request for a hash value (corresponding to a TCP data packet) can be made by using the HARQ ACK related to the HARQ packet which carries the TCP data packet itself in downlink (see Fig. 7).

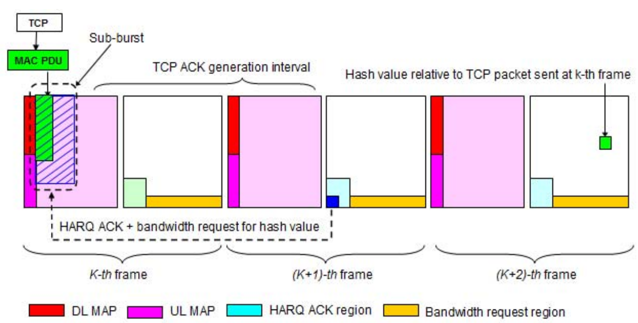

Figure 7. HARQ-based bandwidth request using only one HARQ channel.

A further reduction of the bandwidth request time occurs when using multi-channel HARQ. In this case, more stop-and-wait HARQ channels are established so that the MS sends a higher number of HARQ acknowledgements and therefore HARQ-based bandwidth requests for hash values may be made more frequently. Fig. 8 shows this concept illustrating two HARQ packets destined to the MS can be transmitted in two subsequent downlink subframes which allows sending request for the hash value relative to the TCP packet received by the MS at frame k-th is sent just in that frame by employing the HARQ acknowledgement of the HARQ packet received at (k-1)-th frame.

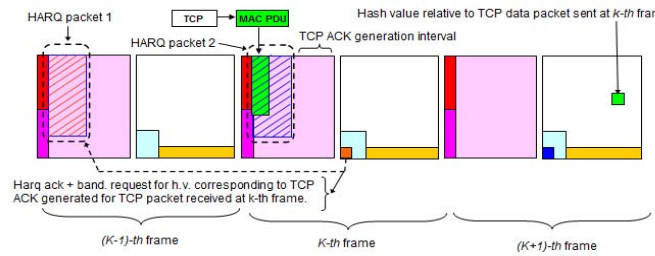

Figure 8. HARQ-based bandwidth request using multichannel HARQ.

It should be underlined that RTT reduction leads to an increase of TCP data transfer performance, as shown in [10].

V. Conclusions and Future Work

The paper proposes a cross-layer strategy to reduce the burden due to TCP ACKs in the WiMAX environment through the introduction of an ARQ Proxy. The ARQ proxy substitutes TCP ACK transmission with a short link layer request sent at the radio link. In WiMAX, the transmission of these link layer requests is designed using tight cooperation from HARQ (default) and ARQ (optional) techniques specified at the physical and link layers respectively.

Performance evaluation results demonstrate good agreement with design objectives. Results confirm the expected ARQ proxy performance in terms of uplink capacity increase, tolerance to higher error rates, and increase in TCP data transfer performance due to reduced RTT.

Future work on the topic includes the extension of the ARQ Proxy optimization to a multihop relaying scenario, currently under standardization in the framework of IEEE 802.16j Working Group.

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