Multi-Resolution Signaling for Multimedia Multicasting

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***Abstract*— This article develops two selective repeat automatic repeat request (SR-ARQ) schemes, which exploit the difference in bit protection levels of M-PSK symbols with Gray code mapping to improve the throughput performance of multimedia multicasting in fading channels. The throughput enhancement is achieved by optimizing the phase offset ratio of nonuniform constellations matched to the difference in QoS requirements for multimedia traffic and link qualities among nodes in a multicast group. The preliminary results of our research are encouraging and provides motivation for further research on leveraging the benefits of nonuniform constellations on higher layers of the protocol stack, i.e., to facilitate efficient multimedia multicasting in wireless networks.**

I. Introduction

In many situations, a rapidly deployed distributed network must be sufficiently flexible in its ability to adapt to constantly changing network topology, support multimedia traffic with varying QoS requirements and facilitate multicast transmission (in addition to unicast and broadcast transmissions) while making efficient use of scarce resources: battery life of light-weight portable nodes and the radio spectrum. In order to support multimedia traffic and conserve energy, adaptive multi-resolution signaling (also known as embedded nonuniform modulation) may be employed to add extra protection to the basic message in a multicast transmission. Multicasting could prove to be an effective way of providing services for a variety of applications that are characterized by close degree of collaboration among a group of nodes (identified by a single destination address). Since the "community of interest" is formed on demand, multicasting feature is desirable for many MANETs deployed in a disaster relief or search and rescue operations.

A fundamental limit to the capacity of single user communication channels was established by Claude Shannon over fifty years ago [1] while Cover [2] showed that, by dividing the traffic into different classes of importance and giving different degrees of protection accordingly, the capacity of broadcast channel may be increased. The basic philosophy in [2] is that the most important information must be received by all receivers, while the less important information is only captured by the "more capable" receivers. This concept [3]–[7]has recently received renewed interest for multicast transmission of multimedia messages to receivers of different capabilities [8], [9] and terrestrial digital video broadcasting standard [10], by using multi-resolution signaling. In [11], a 2/4-PSK nonuniform constellation is used to enhance the throughput on the forward link of cellular CDMA by taking advantage of the power disparities created by power control. Exact bit error rate formulas for computing 4/M-QAM, generalized QAM and PSK hierarchical constellations on AWGN and flat fading channels are provided in [12]–[14]. In [15], the throughput of additional message is maximized through use of adaptive nonuniform PSK-modulation and coding for cellular CDMA over AWGN while maintaining an acceptable error rate for the basic message.

However, the benefits of multi-resolution signaling cannot be fully achieved without a close interaction between the physical layer and higher layers in protocol stack. In order to significantly enhance the network efficiency, knowledge of the channel conditions and node capabilities must be exploited in the design and optimization of network protocols. Much of previous work [8], [9], [13]–[15] have primarily focused on signal design and link-level performance although multicast transmission requires interaction with the higher layers. In this paper we seek to develop and optimize multicasting protocols through careful cross-layer design principles that can appropriately exploit the benefits and overcome the unique challenges presented by adaptive multi-resolution signaling. Specifically, we show that benefits of multi-resolution signaling can be further leveraged at the data link layer through use of our novel selective-repeat ARQ (SR-ARQ) protocols at the sub-packet level. For example, we could attain up to 5dB gain or significant throughput improvement compared to conventional SR-ARQ implementation in a Rayleigh fading environment. Notice that this improvement is achieved without any feedback of the channel quality measurements, without altering the signal constellation at the transmitter or without using error control coding with incremental redundancy. Moreover, in contrast to the scheme proposed in [8], [9], [15], which uses nonuniform PSK to transmit multimedia multicasting where the less capable receiver can only receive the basic message, our objective for multicasting is to provide different levels of protection to the recipients' link according to their QoS requirements, propagation conditions and node capabilities, by determining the optimum phase angles for nonuniform constellation in physical layer and the design of an appropriate SR-ARQ scheme at the MAC layer.

The organization of this paper is as follows. Section II briefly discusses signal design for nonuniform M-PSK constellation that we will use in this paper. Section III details the operation on our SR-ARQ schemes and demonstrates an example that shows the throughput performance and power efficiency with uniform M-PSK constellations. In Section IV, we derive throughput expressions at the subpacket level. Section V provides a discussion on how to optimize for multimedia multicasting. The main points are summarized in Section VI.

II. The Simplified nonuniform M-PSK Constellation Model

The general model of adaptive multi-resolution signaling (also known as embedded nonuniform constellation modulation) can be found in [14]. Here, we introduce some simplifications. For example, consider the nonuniform 8-PSK constellation with $m = \log_2 8 = 3$ hierarchical levels. In Fig. 1, the actual symbols are represented by small circles and Gray labelled. The first level and the second level virtual symbols are represented by "$\times$" and "$+$" respectively. The phase offset angles for general nonuniform M-PSK constellation θ_i, $i = 1, 2, \ldots, m-1$ are simplified as follows:

$$\theta_i = \frac{\pi}{2}\beta^i, \quad i = 1, 2, \ldots, m-1. \tag{1}$$

By fixing β, the ratio of the angles for any subsequent levels of signal constellation hierarchy, to a constant, only a single design parameter needs to be optimized as required in [15], rather than manipulating $m-1$ variables. This facilitates the optimization of phase offsets to meet a prescribed QoS requirement. Also notice that, when $\beta = 0.5$, the system reverts to a uniform constellation.

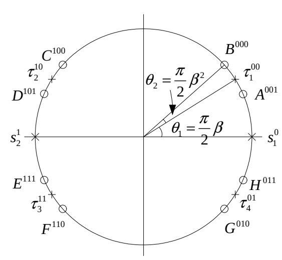
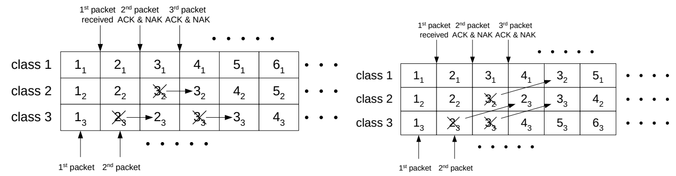


Fig. 1. Nonuniform 8-PSK constellation.

III. Operations of Proposed SR-ARQ Schemes

In the conventional ARQ protocol, multimedia data would simply be transmitted by uniform M-PSK symbols at the packet level. Hence, the required signal-to-noise-ratio (SNR) per bit γ_{req} must be chosen to satisfy the class with the most stringent error requirement.

However, in our proposed ARQ schemes, we take N bits from each class of traffic to form a subpacket. Take 8-PSK for example, the packet consists of 3 subpackets with N bits corresponding to the 3 different classes of messages. If one subpacket was received in error, only this subpacket will be retransmitted using the same error protection, as illustrated in



(a) Scheme-I (b) Scheme-II

Fig. 2. Operations of Scheme-I and II.

Fig. 2(a). Scheme-II is different from Scheme-I in such a way that the negative acknowledged (NAK) subpacket is retransmitted with better error protection. When a transmission error occurs in one particular subpacket, instead of retransmitting it in the same error protection level, we will schedule the retransmission in the next higher class. If the retransmission fails again, the second retransmission will be scheduled to an even higher class, so on and so forth. This operation procedure is illustrated in Fig. 2(b).

IV. Throughput Performance of SR-ARQ Scheme-I and Scheme-II

In this section, we will derive the throughput expressions for each class of subpacket for both Scheme-I and Scheme-II. Let us first consider the Scheme-II. For simplicity, we assume an 8-PSK modulation (either uniform or nonuniform) scheme is used with three different bit classes, and assuming sources for all subpacket classes are infinite and no error correction coding is employed. Denote the error rate for subpacket class i by P_{spi}. The normalized average number of transmissions for subpacket class 1 can be computed as

$$\begin{aligned} \bar{n}_1 &= (1-P_{sp1})\sum_{i=1}^{\infty} iP_{sp1}^{i-1} \\ &= (1-P_{sp1})\frac{1}{(1-P_{sp1})^2} = \frac{1}{1-P_{sp1}}. \end{aligned} \tag{2}$$

Hence, the throughput of subpacket class 1, denoted by $S_1^{(1)}$, is simply the reciprocal of $\bar{n}_1$, i.e.,

$$S_1^{(1)} = \frac{1}{\bar{n}_1} = 1 - P_{sp1}. \tag{3}$$

The normalized average number of transmissions for subpacket class 2 is given by

$$\begin{aligned} \bar{n}_2 &= 1 - P_{sp2} + P_{sp2}(1-P_{sp1})\sum_{i=2}^{\infty} iP_{sp1}^{i-2} \\ &= \frac{1-P_{sp1}+P_{sp2}}{1-P_{sp1}}. \end{aligned} \tag{4}$$

Hence, we obtain

$$S_2^{(2)} = \frac{1}{\bar{n}_2} = \frac{1-P_{sp1}}{1-P_{sp1}+P_{sp2}}. \tag{5}$$

Similarly, the average number of retransmission times of subpacket class 3 for Scheme-II is given by

$$\begin{aligned}\bar{n}_3 &= 1 - P_{sp3} + 2P_{sp3}(1 - P_{sp2}) + \\ &\quad P_{sp3}P_{sp2}(1 - P_{sp1}) \sum_{i=3}^{\infty} i P_{sp1}^{i-3} \\ &= \frac{(1 - P_{sp1})(1 + P_{sp3}) + P_{sp2}P_{sp3}}{1 - P_{sp1}}. \quad (6)\end{aligned}$$

So the throughput of subpacket class 3 is given by

$$S_3^{(2)} = \frac{1}{\bar{n}_3} = \frac{1 - P_{sp1}}{(1 - P_{sp1})(1 + P_{sp3}) + P_{sp2}P_{sp3}}. \quad (7)$$

On the other hand, the throughput of subpacket classes of Scheme-I are simply

$$S_1^{(1)} = 1 - P_{sp1}, \quad (8)$$

$$S_2^{(1)} = 1 - P_{sp2}, \quad (9)$$

$$S_3^{(1)} = 1 - P_{sp3}. \quad (10)$$

The derivations for (8), (9), and (10) are similar to that of (3).

Now let us compare the throughput performance of Scheme-I and Scheme-II with the conventional ARQ scheme. For conventional ARQ scheme using M-PSK, every symbol is representing $\log_2 M$ bits. Therefore, the average BER can be calculated as

$$\bar{P}_b = \frac{1}{\log_2 M} \sum_{i=1}^{\log_2 M} P_b^i, \quad (11)$$

where P_b^i is the BER of each particular bit in the M-PSK symbol. The exact BER expression of P_b^i can be found in [14]. In order to calculate the throughput of Scheme-I, Scheme-II, and the conventional ARQ scheme, we need to get the required SNR for each subpacket class. However, although the algorithm for computing BER as a function of β and SNR is available, it is somewhat a complicated expression. Therefore, it is very difficult to invert this algorithm to compute the required SNR to meet the BER requirement for different β values. In this paper, we use the following expression to approximate the BER of nonuniform M-PSK modulation schemes

$$P_{e,\beta}^{(i)} = a_\beta^{(i)} e^{-b_\beta^{(i)} \gamma^{(i)}} + c_\beta^{(i)} e^{-2b_\beta^{(i)} \gamma^{(i)}}. \quad (12)$$

In (12), $a_\beta^{(i)}$, $b_\beta^{(i)}$, and $c_\beta^{(i)}$ are three parameters to be determined such that the difference between the exact BER and the approximation is minimized in the sense of mean square error. Notation i corresponds to the ith bit in a nonuniform constellation symbol, while $\gamma^{(i)}$ denotes the SNR. We employed Quasi-Newton BFGS algorithm to perform the curve fitting. Moreover, we can further simplify the $a_\beta^{(i)}$, $b_\beta^{(i)}$, and $c_\beta^{(i)}$ by doing another curve fitting by using the following 3rd order polynomial expression:

$$p_1\beta^3 + p_2\beta^2 + p_3\beta + p_4, \quad (13)$$

where p_1, p_2, p_3, and p_4 are constants to be determined. Table I shows the 3rd order polynomial coefficients for $a_\beta^{(i)}$, $b_\beta^{(i)}$, and $c_\beta^{(i)}$. To compare the exact BER and the approximated BER using equation (12), we plot the exact BER and approximated BER curves over an AWGN channel in Fig. 3 and Fig. 4 for $\beta = 0.3$ and $\beta = 0.47$, respectively.

	(i)	p_1	p_2	p_3	p_4
a	(1)	−0.76307	1.5372	−0.79287	0.18306
	(2)	−4.2536	4.6811	−1.6456	281.729
	(3)	4.7056	−2.4609	4.41597	0.41012
b	(1)	9.6987	−11.795	2.02	0.87874
	(2)	−2.0114	1.2986	−0.16576	−0.0024344
	(3)	3.6044	−1.8742	0.40372	0.026842
c	(1)	25.27	−26.115	7.2969	0.13772
	(2)	3.5188	−3.082	−0.46332	−0.13291
	(3)	−2.9034	−1.9248	−0.13291	0.15968

TABLE I

3RD ORDER POLYNOMIAL COEFFICIENTS FOR a, b, AND c

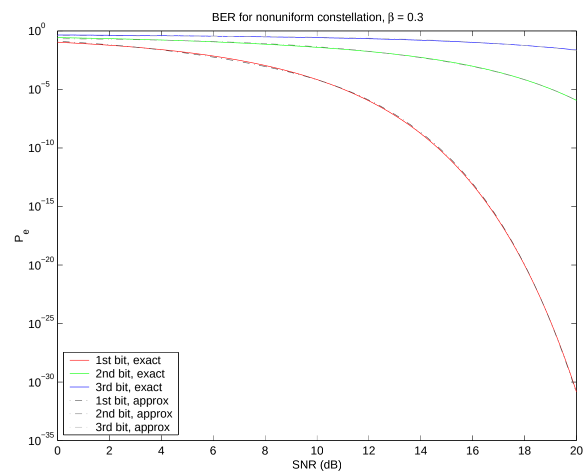


Fig. 3. Exact BER and Approximated BER, $\beta = 0.30$

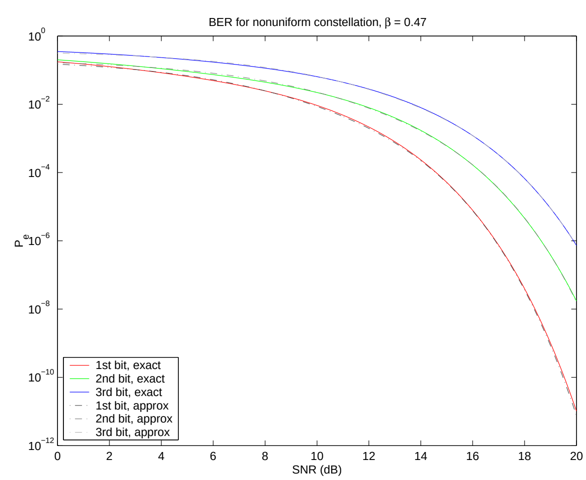


Fig. 4. Exact BER and Approximated BER, $\beta = 0.47$

The reason behind using (12) is that we can easily invert (12) to get the required SNR γ_{req} if the QoS requirement P_e is specified. Let $y_\beta^{(i)} = e^{-b_\beta^{(i)}\gamma}$, then (12) reduces to a quadratic equation. Since $y_\beta^{(i)}$ is positive, solving this quadratic equation,

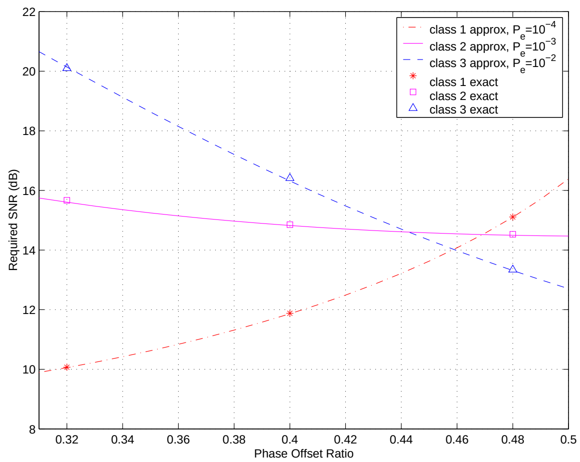


Fig. 5. Required SNR for different classes of services.

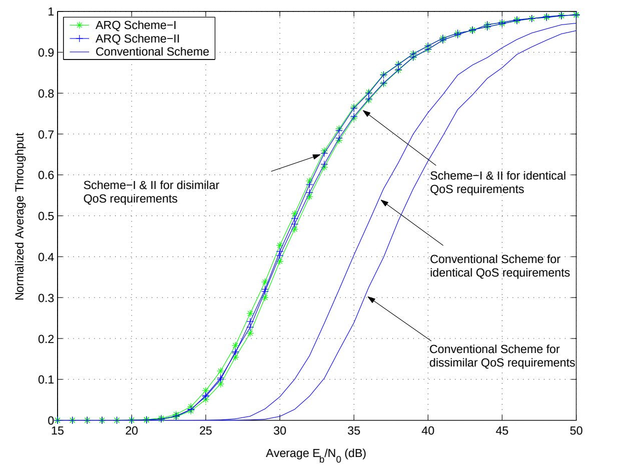


Fig. 6. Throughput comparison between proposed ARQ schemes and the conventional scheme.

we obtain

$$y_\beta^{(i)} = \frac{-a_\beta^{(i)} + \sqrt{(a_\beta^{(i)})^2 + 4c_\beta^{(i)} P_e}}{2c_\beta^{(i)}}. \tag{14}$$

Once we compute $y^{(i)}$, the required $\gamma_{req}^{(i)}$ is simply given by

$$\gamma_{req}^{(i)}(\beta) = -\frac{1}{b_\beta^{(i)}} \ln y_\beta^{(i)}, \quad i = 1, 2, 3 \dots \tag{15}$$

We plot the required SNR/bit for different classes of services as functions of the phase offset ratio β in Fig. 5. The discrepancy between the curves obtained using the exact and the approximate average BER formulas are indistinguishable.

If the BER requirement for all traffic is 10^{-3}, we have $\gamma_{req}^{(1)} = 14.5$dB, $\gamma_{req}^{(2)} = 14.5$dB, and $\gamma_{req}^{(3)} = 15.3$dB. Although not shown here, the required SNR for average BER$= 10^{-3}$ of 8-PSK uniform constellation is $\gamma_{req}^{(avg)} = 14.8$dB. Since the conventional scheme is doing symbol-by-symbol detection, the required SNR for a symbol is given by

$$\gamma_{req}^{(symbol)} = \log_2 M \times \gamma_{req}^{(avg)} = 19.6\,\text{dB}. \tag{16}$$

Therefore, by using Scheme-I and Scheme-II on subpacket level, we have more than 4dB improvement on required SNR even only for uniform constellation. We simulated 10,000 packets in a Ricean fading channel with Ricean factor $K = 3$ and model the subpacket error process in a simplistic way: a subpacket is considered error free if all the bits received with SNR above $\gamma_{req}^{(i)}$. Suppose that the length of each subpacket is $N = 32$. If at least one out of N bits is below $\gamma_{req}^{(i)}$, then the subpacket must be retransmitted. Therefore, the subpacket error rate is computed as

$$P_{sp}^{(i)} = \Pr\left\{\frac{\text{Symbols in a subpacket above } \gamma_{req}^{(i)}}{N} < 1\right\}. \tag{17}$$

The simulation results are plotted in Fig. 6, and are marked by "identical QoS requirements." We see that the throughput improvement of our ARQ schemes is dramatic. For the same throughput performance, we have up to 5dB improvement in average signal power. We also observe that Scheme-II performs slightly better than Scheme-I, although the difference is not significant in this case. The reason is that the difference between $\gamma_{req}^{(i)}$ for uniform constellation is quite minor.

V. Optimizing β for Multimedia Multicasting

Let us consider the throughput improvement of our proposed ARQ schemes with nonuniform constellation when they support multimedia multicasting. For instance, there are three different classes of traffics, each of which has BER requirement 10^{-4}, 10^{-3}, and 10^{-2} respectively. In order to meet the BER requirement by using nonuniform constellation, we must optimize the phase offset ratio β. One criteria we can use to optimize β is as follows.

$$\begin{aligned} &\arg\min_\beta \left\{\max_i \left\{\gamma_{req}^{(i)}\right\}\right\} \\ \text{s.t.}\quad & P_b^{(1)} \le 10^{-4} \\ & P_b^{(2)} \le 10^{-3} \\ & P_b^{(3)} \le 10^{-2} \\ & \beta \in (0, 0.5],\ i \in \{1, 2, 3\} \end{aligned} \tag{18}$$

(18) suggests that we should choose the most power-efficient phase offset ratio β while meeting the service requirements of all three classes of services. From (15), we can determine that $\beta = 0.47$ is the optimal solution (see Fig. 5 for graphical illustration). The required SNR for three classes of services when $\beta = 0.47$ are 14.6dB, 14.5dB, and 13.7dB respectively. For the conventional scheme, since all different classes of traffic are randomly assigned to the bits of 8-PSK symbols, the average BER has to meet the most stringent service requirement 10^{-4}. Although not shown in this paper, we found this required E_b/N_0 is 16.74dB. Using the same simulation method as in the previous section, we plot the throughput performance of Scheme-I, Scheme-II, and the conventional ARQ scheme in Fig. 6.

Compared with the scenario where all classes have identical QoS requirements, we found that Scheme-I and Scheme-II can achieve even higher throughput gain when supporting multimedia multicasting. Notice, however, that the average throughput of Scheme-II is a little bit higher than Scheme-I for the optimized $\beta = 0.47$. This reflects the fact that Scheme-II, with additional complexity in MAC layer, does not necessarily outperform Scheme-I. This is because $\gamma_{req}^{(3)}$ is the lowest one among three classes. Therefore, there is no benefit in using higher subpacket classes to do the failed packet retransmission for subpacket classes 3. The necessary condition for Scheme-II to perform better is

$$\gamma_{req}^{(1)} \leq \gamma_{req}^{(2)} \leq \gamma_{req}^{(3)}. \tag{19}$$

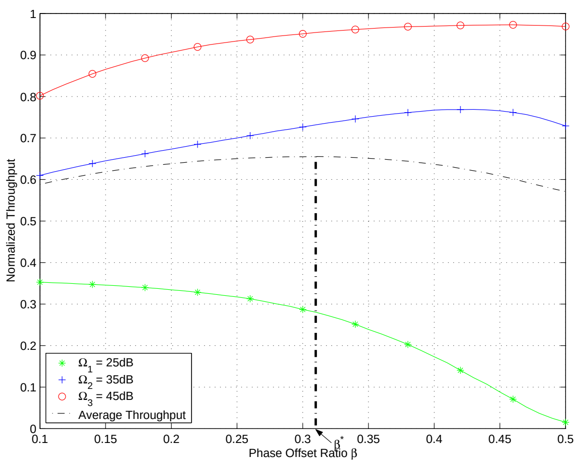


Fig. 7. Average throughput for nodes with different link qualities.

In a practical MANET, however, the channels between the nodes may differ considerably because of differences in propagation characteristics and interference, and due to the differing capabilities of the heterogeneous nodes themselves. For example, small hand-held devices carried by rescue personnel may only have one or two array elements which impose a limit on the degrees of freedom available for allocating antenna beams. Perhaps only certain users served by a particular node may require large bandwidths without significantly affecting the reliability and quality of voice communications (basic message) between their team members.

Therefore, when optimizing β, we also need to take into account the different link qualities of the receiving nodes. For example, if there are 3 receiving nodes and the average SNR for them are 25dB, 35dB, and 45dB respectively. Suppose that the system uses Scheme-II. Again, the average throughput for three nodes are shown in Fig. 7. From the transmitter point of view, one strategy is to choose β such that the throughput is maximized. From Fig. 7 we can see the optimal solution $\beta^* = 0.31$ in this particular case.

In summary, there are many aspects to be considered when optimizing the phase offset ratio β. One could choose to maximize the system throughput, minimize the power consumption, or find a balance between these two. The difference of link qualities of receiving nodes is another important factor to be considered too. Moreover, how to determine the phase offset ratio for a large-scale network in real time is another challenging task as well, and this would be part of our future work.

VI. Conclusion

In this paper, we propose two novel SR-ARQ schemes at the subpacket levels for leveraging the benefits of nonuniform M-PSK constellations at the data link layer. We have shown through selected numerical examples that both of the ARQ schemes have significant improvements on system throughput compared to the conventional SR-ARQ scheme at the packet level. We also consider the cross-layer issue that deals with the optimization of phase offset ratio β involving physical, network, and application layers constraints. The preliminary results are encouraging and motivates us for further research on leveraging the benefits of nonuniform constellations on higher layers of the protocol stack such that it facilitates efficient multimedia multicasting in distributed wireless networks.

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