SICTA Modifications with Single Memory Location and Resistant to Cancellation Errors

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Abstract. In this paper we consider a cross-layer MAC-PHY technique that combines the collision resolution tree algorithm (TA) with the possibility of successive interference cancellation (SIC). The overview of the previous work shows that no simple protocol has been proposed to use a single memory location for the captured signal. We, consequently, propose two such protocols that demonstrate the throughput - implementation complexity trade-off. Further, we address the system operation during which interference cancellation errors are possible. We propose the third protocol that is resistant to cancellation errors. A simple yet effective technique is applied to address the throughput performance of all three protocols to demonstrate their superiority over known conventional TA protocols.

1 Introduction and Background

1.1 Conventional Random MAC Protocols

Cross-layer techniques enable telecommunication systems to achieve higher data rates than it is possible with the conventional OSI model interaction. In particular, the mutual collaboration of *physical* (PHY) and *media access control* (MAC) layers has proved to be very promising as MAC layer is practically a bottleneck of the modern telecommunication systems. A multiplicity of MAC protocols is known and analyzed [1], [2], thus leaving developers with a wide choice. Random MAC protocols are frequently used to cope with bursty traffic and to provide reasonably low packet delay even when a user population is high.

Broadly speaking, each random MAC protocol defines a *channel access algorithm* (CAA) and a *collision resolution algorithm* (CRA). The former arbitrates access to the shared broadcast channel, whereas the latter resolves the packet collisions (i.e. simultaneous transmissions of two or more data packets), whenever they arise. In ALOHA and ALOHA-based protocols, such as *diversity slotted aloha* (DSA), *binary exponential backoff* (BEB), *carrier sense multiple access* (CSMA) and others no particular CRA is specified. These protocols are generally easy to implement and once a collision occurs their underlying idea is to defer the subsequent packet retransmission to some future time in a 'hope' that the communications channel becomes idle.

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By contrast, *tree algorithm* (TA) proposed in [3] and [4] defines a CRA to specifically address the collision resolution process and, consequently, to achieve higher performance. The performance of the original *standard tree algorithm* (STA) was enhanced by the *modified tree algorithm* (MTA). We refer to the STA and the MTA as to the *conventional* TAs in what follows. Each TA may incorporate one of three alternative CAAs, which are *gated* access, *window* access or *free* access.

According to the gated CAA the new data packets that arrive during the so-called *collision resolution interval* (CRI) are deferred. Once current collision is resolved, all the deferred packets are transmitted simultaneously to create the following collision and to start a new CRI. Window CAA is a generalization of the gated access scheme for the case when a new CRI is formed not by all the packets that arrive during the previous CRI, but by those arriving within a specified time window. The proper adjustment of this window may result in the higher performance of the TA. The gated and the window CAAs are together referred to as *blocked access* schemes. Finally, free CAA assumes the packet is transmitted immediately following its arrival.

1.2 Cross-Layer MAC-PHY Approaches

All conventional random MAC protocols assume that once a collision occurs no meaningful data packet could be recovered from it. However, for the wireless communications channel a *successive interference cancellation* (SIC) technique is known, which is a nonlinear type of a multiuser detection scheme, where users signals are decoded successively. More specifically, SIC first tries to detect and demodulate the strongest user signal currently present in the composite captured signal. After it is done, this signal contribution to the original signal is recreated and subtracted from it. A new composite signal is thus produced, which could be again the input for the iterative SIC procedure.

In [5] it was shown that SIC is capable of approaching the theoretical limits for an AWGN channel and its *cancellation error* was introduced and estimated. A cancellation error for a user is defined as its residual signal in the remaining composite signal after the subtraction of the recreated signal. The main reasons of the cancellation error are imperfect (amplitude and phase) channel estimation and incorrect bit decisions.

In [6] a concept of *successive interference cancellation in a tree algorithm* (SICTA) was first proposed to combine the advantages of SIC and conventional TAs. A new protocol was described and analyzed that adopts SIC to reuse the collision signals that are stored in a (potentially) unbounded memory. The main performance metrics considered were packet delay and *maximum stable throughput* (MST), which is defined as the highest possible (Poisson) arrival rate that still yields a finite packet delay with probability one. Note, that the STA and the MTA have the MST of 0.346 and 0.375, respectively, for binary tree and fair splitting (left and right tree branches are selected with equal probability). The proposed SICTA protocol has the MST of 0.693, which is twice that of the STA.

All known SICTA modifications theoretically required an unbounded memory storage for the received collision signals. By contrast, in [7] the performance of a novel TA with SIC property was investigated for which a single memory location suffices. Additionally, this protocol considered free CAA and was analyzed for a variety of the Markovian arrival processes and the error-free channel. The MST of the proposed protocol was shown to be 0.5698 for Poisson arrivals by using the additional control field/bit with separate feedback, indicating whether the packet is transmitted for the first time.

Motivated by the above work, we notice that the MST performance of original SICTA protocol [6] is yet to be evaluated under the single memory location assumption. Filling this gap results in two modifications of the original SICTA protocol as in [8]. First modification cancels only successful transmissions and, therefore, relies on a simpler SIC PHY scheme. Second modification cancels both collision signals and successful transmissions and, therefore, demonstrates the higher MST for the cost of a more difficult SIC implementation. Finally, following [9] we show that the introduced protocols suffer from a 'perpetual splitting' phenomenon when a probability of a cancellation error [5] is nonzero. We finally extend our model to account for the possible cancellation errors and modify the protocol operation to acquire robustness to the imperfect interference cancellation without severe tree truncation as in [9] and [10].

The rest of the paper is structured as follows. In Section II we formulate the assumptions of the reference information theoretical model and speculate on its variations in the aforementioned papers. Here we also describe the underlying idea of known protocols as well as of the proposed modifications. Section III conducts the MST analysis of the introduced protocols. In Section IV we compare the theoretical results and summarize the paper.

2 System Model and Protocols

2.1 Reference Information Theoretical Model

Following the multitude of works, e.g. [1], [2] and [11] we formulate a set of assumptions about the communications channel and the way users access it:

Assumption 1. The system time is slotted into equal slots. The duration of each slot is a unit of the system time, which is exactly the transmission time of one data packet. Each slot is assigned an integer nonnegative number and number t slot corresponds to the time interval of $[t, t+1)$. Hereinafter we refer to number t slot simply as slot t for the sake of brevity. Slot borders are known to all the users and each user is restricted to start its packet transmission only in the beginning of a slot.

Assumption 2. In each slot any and only one of the following error-free events may occur (channel-PHY feedback):

– Only one user transmits (**S** event - success);
– None of the users transmit (**E** event - empty);
– Two or more users transmit (**C** event - collision).

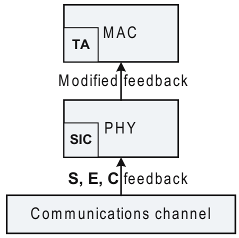

Fig. 1. Various feedback types

Assumption 3. When monitoring the channel activity the MAC layer of a user is notified of the channel event by the end of the current slot. The size of the PHY-MAC feedback (see Fig. 1) a user receives is subject to some variations below.

Assumption 4. There is an infinite user population, generating packets that are assumed to be unique. Each user is supplied with a buffer sufficient to store only one packet. The packet is stored from the instant of time it arrived into the system to the instant of time it is successfully transmitted. Packet inter-arrival times are assumed to be statistically independent random variables which are distributed exponentially with the mean value of $\frac{1}{\lambda}$. Thus, λ is the arrival rate of the new packets into the system. Notice, that infinite population provides a pessimistic estimation for a finite population system by considering each packet to be a virtual station.

2.2 Various PHY-MAC Feedback Types

The conventional STA with gated access requires only 'collision' - 'no collision' PHY-MAC feedback from the receiver (see **Assumption 3**) for its proper operation. New data packets that arrive during the previous CRI are transmitted in the first slot of the following CRI. If 'no collision' feedback is received for this initial slot, the CRI ends. Otherwise, each of the collided users flips a (biased) coin to choose the right subset with probability p and the left subset with probability $1 - p$ (see Fig. 2(a)). The procedure is repeated recursively until all the packets are received successfully. The example collision resolution tree in Fig. 2(a) comprises 7 slots, which is exactly the CRI length. For binary STA fair splitting with $p = 0.5$ is optimal and yields the MST of 0.346 [2], [12].

We notice that in the example collision resolution tree (see Fig. 2(a)) the collision in slot 5 is deterministic, since the collision in slot 3 is followed by the empty right slot 4, which means that all the collided users have chosen the left subset. In [3] and [4] a 'level skipping' was proposed to omit slot 5 and proceed directly to the next tree level. Therefore, the CRI length reduces to 6 slots (see Fig. 2(b)) instead of 7. The conventional binary MTA with gated access uses this idea and results in the MST of 0.375 for fair splitting. However, a biased splitting with $p = 0.582$ is optimal and yields the MST of 0.381 [12]. We finally notice that MTA requires the extended ternary 'success' - 'empty' - 'collision' PHY-MAC feedback to enable the discussed improvement.

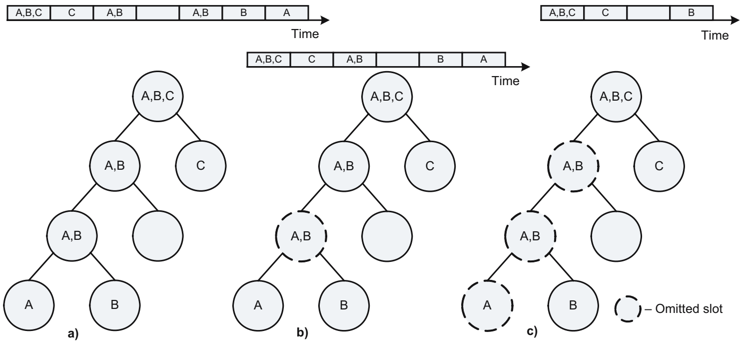

Fig. 2. STA (left), MTA (middle) and SICTA (right) examples

In the original SICTA protocol the receiver is supplied with the unbounded memory to store the collision signals. Consider the example in Fig. 2(c) where the CRI length is only 4 slots. The contents of the corresponding left slot is determined by canceling the interference from slot 1 after the successful reception of signal C in slot 2. Following the notation from [6], we denote the cancellation procedure as $\tilde{Y}_1 = Y_1 - X_C$. As slot 3 is empty the corresponding left slot is skipped following the rules of the MTA. Finally, the successful reception of signal B in slot 4 immediately yields the recovery of signal A by $\tilde{\tilde{Y}}_1 = \tilde{Y}_1 - X_B = Y_1 - X_C - X_B$.

As the entire left subtree of the STA is omitted by the original SICTA protocol, it results in the MST of 0.693, which is twice the MST of the STA. Additionally, SICTA requires extended k - 'empty' - 'collision' PHY-MAC feedback, where k is the number of successfully decoded packets plus the number of left slots identified as being empty after the SIC procedure.

Despite its high performance, SICTA is vulnerable to noise and imperfect interference cancellation in the error-prone communications channel. Indeed, suppose in Fig. 2(c) the last cancellation operation is degraded by the noise term N, that is $\tilde{\tilde{Y}}_1 = \tilde{Y}_1 - X_B + N$. If N is sufficiently large the signal A may not be restored and the collision resolution continues. Eventually, after A is transmitted successfully, the noise energy level may still be sufficiently high to lead receiver into believing there is another collision in the left slot. The protocol will require nonexistent users to further split until some external entity terminates it.

To overcome the above deadlock the SICTA/FS protocol was introduced to truncate the SICTA collision resolution tree after the first success [9]. For the operation of this protocol the ternary 'success' - 'empty' - 'collision' PHY-MAC feedback again suffices. However, during SICTA/FS analysis the **Assumption 4** has been replaced with the finite user population assumption, which considerably changes the system model and makes the derived MST value incomparable with those for SICTA and conventional TAs. (G)BEB-SICTA/FS protocols [13] also operate in the framework of this modified system model. Furthermore, SICTA/F1 protocol [10] for harsh wireless channel truncates the collision resolution tree after either first success or empty slot and, therefore, requires only 'collision' - 'no collision' PHY-MAC feedback.

2.3 Single Memory Location

Supplying the receiver with the unbounded memory storage for the collision signals is practically infeasible. Accounting for this fact, the question of the SICTA operation with the single memory location was first addressed in [7]. As we are interested in the similar investigation we extend the system model as follows.

Assumption 5. The receiver is able to store a single signal for which a single memory location is dedicated.

Importantly, in [7] each data packet was supplied with an extra field/bit with separate feedback, indicating whether the packet is transmitted for the first time. This again makes the derived MST incomparable with those for SICTA and conventional TAs as the system model has changed. Finally, in [8] two modifications of the FCFS protocol has been introduced, which conform to the derived system model and have the MST of 0.6048 and 0.6173, respectively. As mentioned above, the main drawback of the FCFS-based protocol is (potentially) infinite timer granularity [1], which may be difficult to achieve in the real systems.

Below we concentrate on the gated access SICTA with the single memory location. As in [8], we observe two implementation possibilities for the SIC operation. In the first straightforward scenario after the successful transmission has been detected and demodulated by SICTA, its contribution to the original signal is regenerated and subtracted from the overall received signal in memory (see Fig. 3(a)). Or, alternatively, a cancellation operation is only possible when a transmission is successful. We term the modification of SICTA that use this property SICTA with *success cancellation* (SICTA/SC). In some practical systems it may be also possible to cancel the collision signal from memory, even though the received signal is not detected and demodulated (see Fig. 3(b)). Clearly, this second implementation option impacts the performance of the protocol, which we term SICTA with *success and collision cancellation* (SICTA/SCC).

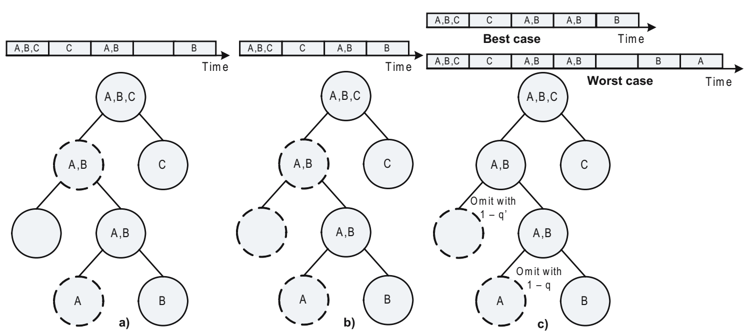

Fig. 3. SICTA/SC (left), SICTA/SCC (middle) and R-SICTA/SCC (right) examples

2.4 Presence of Cancellation Errors

We remind that in practical SIC schemes a cancellation error is possible [5], which is the residual signal in the remaining signal after the SIC procedure. For instance, after the cancellation of the signal A from the composite signal $X_A + X_B$ the resulting signal contains $\tilde{Y} = X_B + N_A$, where N_A is the residual signal A. After the subsequent cancellation of signal B we similarly obtain $\tilde{\tilde{Y}} = N_A + N_B$. If the $N_A + N_B$ energy level is sufficiently high the receiver incorrectly decides that the slot is not empty, but rather there is a collision between the nonexistent users. Below we assume that due to cancellation errors the interference is unsuccessful with some constant probability. That is, with this probability receiver obtains a meaningless signal after the next interference cancellation. In practice this probability could be derived as the worst-case estimate of the SIC operation.

Assumption 6. The interference cancellation is imperfect in a sense that after the successful signal is canceled from the composite signal the resulting signal contains a meaningless signal with probability q. Similarly, after the collision signal is canceled from the composite signal (following the second SIC implementation possibility) the resulting signal contains a meaningless signal with probability q'. We expect that in practice $q' \geq q$, that is, it is more difficult to cancel the collision signal than the successful signal.

The third protocol we propose is resistant to the imperfect cancellation of both types for the cost of its MST performance (see Fig. 3(c)). Basically, it refrains from skipping some collision slots like slot 3, whereas SICTA/SC and SICTA/SCC do. This allows avoiding 'perpetual splitting' phenomenon. We term this protocol *robust* SICTA/SCC (R-SICTA/SCC). Notice, that the rules for R-SICTA/SC that cancels only successfully received signals could be derived similarly, but this is left out of scope of this paper. In Fig. 3(c) the best case timeline corresponds to the case when both interference cancellation operations were successful, whereas the worst case timeline demonstrates both unsuccessful cancellations.

3 Performance Analysis

3.1 Example MTA Analysis

In order to demonstrate the approach that we use below to derive the MST of the proposed protocols, we firstly focus on the analysis of the MTA. Denote by τ the random CRI length. Formally, the conditional expectation $T_k = E[\tau|$a collision of multiplicity k is resolved] gives the average CRI length for a collision of multiplicity k. In [3] it was shown that using the ratio $\frac{k}{T_k}$ the following bounds on the STA MST (R_{STA}) could be established:

$$\liminf_{k \to \infty} \frac{k}{T_k} < R_{STA} < \limsup_{k \to \infty} \frac{k}{T_k}. \quad (1)$$

The estimates for R_{STA} were summarized by [14] and the following refined figures were given:

$$0.34657320 < R_{STA} < 0.34657397. \quad (2)$$

As $\limsup\limits_{k\to\infty} \frac{k}{T_k} - \liminf\limits_{k\to\infty} \frac{k}{T_k} = 0.00000077$ we follow [14] to notice:

$$R_{STA} \cong \liminf_{k\to\infty} \frac{k}{T_k} \cong \limsup_{k\to\infty} \frac{k}{T_k} \cong \frac{ln2}{2}. \tag{3}$$

We denote the number of the collision resolution tree nodes in a STA by n. The number of successful, collision and empty slots during a CRI is denoted by n_s, n_c and n_e, respectively. As $n_s + n_c + n_e = n$, we use [11] to obtain:

$$\begin{aligned} n_s &= k, \\ n_c &= \frac{n-1}{2}, \\ n_e &= \frac{n+1}{2} - k. \end{aligned} \tag{4}$$

Now we calculate the expected number of nodes (expected CRI length) in the MTA tree $E[m]$ by subtracting the omitted nodes (Fig. 4(a)):

$$E[m] = E[n] - \frac{1}{2}E[n_e] = \frac{3}{4}E[n] + \frac{k}{2} - \frac{1}{4}. \tag{5}$$

That is, $T_k^{MTA} = \frac{3}{4}T_k^{STA} + \frac{k}{2} - \frac{1}{4}$. Taking the $\liminf\limits_{k\to\infty}$ and $\limsup\limits_{k\to\infty}$ of (5) and accounting for (3) we establish:

$$R_{MTA} \cong \frac{1}{\frac{3}{4R_{STA}} + \frac{1}{2}} \approx 0.375. \tag{6}$$

3.2 SICTA/SC and SICTA/SCC

Here we consider perfect interference cancellation (**Assumptions 1 - 5** of the system model) and firstly derive the MST of the SICTA/SC protocol that cancels only successfully received signals. Analogously to the MTA analysis, we calculate the expected number of nodes (expected CRI length) in the SICTA/SC tree $E[m]$ by subtracting the omitted nodes (Fig. 4(a,b)) and accounting for (4):

$$E[m] = E[n] - \frac{1}{2}E[n_e] - \frac{1}{2}E[n_s] = \frac{3}{4}E[n] - \frac{1}{4}. \tag{7}$$

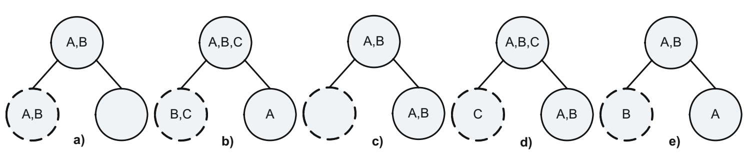

Fig. 4. Collision resolution tree examples for MST derivation

Using (3) the final expression for the MST of the SICTA/SC ($R_{SICTA/SC}$) is obtained as follows:

$$R_{SICTA/SC} \cong \frac{4}{3} R_{STA} \approx 0.462. \tag{8}$$

Below we derive the MST of the SICTA/SCC protocol that cancels both successful and collision signals. We again calculate the expected number of nodes (expected CRI length) in the SICTA/SCC tree $E[m]$ by subtracting the omitted nodes (Fig. 4(a,b,c,d)) and accounting for (4). Notice that on average we have to add $\frac{1}{2}E[n_2]$ term, where n_2 is the number of collisions of size two during the CRI (Fig. 4(e)), as it was subtracted twice (Fig. 4(b,d)):

$$E[m] = E[n - n_e - n_s] + \frac{1}{2}E[n_2] = \frac{1}{2}E[n] - \frac{1}{2} + \frac{1}{2}E[n_2]. \tag{9}$$

Following [14] we establish the bounds on the $\frac{E[n_2]}{k}$:

$$\limsup_{k\to\infty} \frac{E[n_2]}{k} < 0.721355,$$
$$\liminf_{k\to\infty} \frac{E[n_2]}{k} > 0.721340. \tag{10}$$

Note that $\limsup\limits_{k\to\infty} \frac{E[n_2]}{k} = \liminf\limits_{k\to\infty} \frac{E[n_2]}{k} = \gamma$ with the accuracy of three decimal digits and $\gamma = 0.721$. Using (3) and (10) the final expression for the MST of the SICTA/SCC ($R_{SICTA/SCC}$) is obtained as follows:

$$R_{SICTA/SCC} \cong \frac{2}{\frac{1}{R_{STA}} + \gamma} \approx 0.5545. \tag{11}$$

3.3 R-SICTA/SCC

We now consider imperfect interference cancellation (**Assumptions 1 - 6** of the system model) and derive the MST of the R-SICTA/SCC protocol that cancels both successful and collision signals in the presence of cancellation errors.

Remember (**Assumption 6**) that after the successful captured signal is canceled from the stored signal the resulting signal contains a meaningless signal with probability q and after the collision captured signal is canceled from the stored signal the resulting signal contains a meaningless signal with probability q' ($q' \geq q$). Below we calculate the expected number of nodes (expected CRI length) in the R-SICTA/SCC tree $E[m]$ by subtracting the omitted nodes (Fig. 4(a) with probability 1, Fig. 4(c,d) with probability $1 - q'$ and Fig. 4(e) with probability $1 - q$) and accounting for (4). We also account for n_2, that is, the number of collisions of size two during the CRI, to obtain the following:

$$E[m] = (\frac{1}{2} + \frac{1}{4}q')E[n] - \frac{1}{2} + \frac{1}{4}q' + \frac{k}{2} - \frac{1}{2}(q' - q)E[n_2]. \tag{12}$$

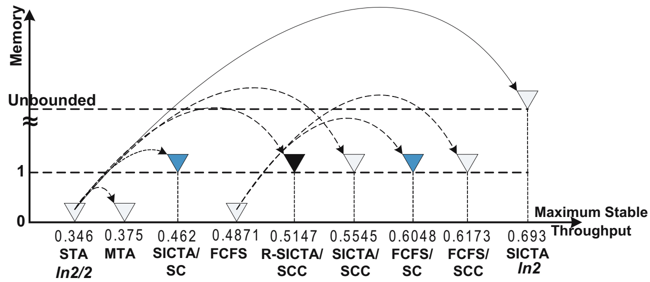

Fig. 5. MST comparison and relations of blocked access protocols

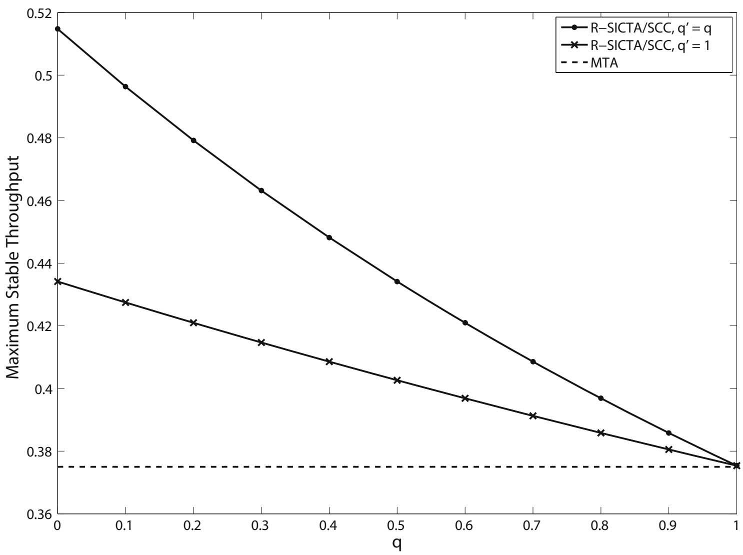

Fig. 6. R-SICTA/SCC MST for imperfect SIC

Using (3) and (10) the final expression for the MST of the R-SICTA/SCC ($R_{R-SICTA/SCC}$) is obtained as follows:

$$R_{R-SICTA/SCC} \cong \frac{4}{\frac{2+q'}{R_{STA}} + 2 - 2(q'-q)\gamma}. \tag{13}$$

Clearly, when $q' = q = 0$, $R_{R-SICTA/SC} \approx 0.5147$. We further emphasize two important special cases of the q' behavior (see Fig. 6). First is when $q' = q$ and $R_{R-SICTA/SCC} \cong \frac{4}{\frac{2+q}{R_{STA}}+2}$. Second is when $q' = 1$ and R-SICTA/SC protocol operates, for which $R_{R-SICTA/SC} \cong \frac{4}{\frac{3}{R_{STA}}+2-2(1-q)\gamma}$.

4 Comparison and Conclusions

The cross-layer combination of the PHY SIC technique and the MAC TA is prominent as it enables higher system throughput for the cost of moderate implementation complexity. A family of protocols that follow this approach is known, of which only the original SICTA has the provable MST of 0.693 in the infinite population model (see Fig. 5). Unfortunately, SICTA requires unbounded memory to store the captured collision signals that complicates its practical implementation. By contrast, some works are known to address similar protocols with a single memory location. However, neither addresses the behavior of the original SICTA protocol with a memory restriction.

We begin with the investigation of the single memory location SICTA that results in two distinct implementation possibilities. The former enables SIC only after the successful signal has been captured. The latter cancels both successful and collision signals to, consequently, achieve higher MST for the cost of a more complex PHY. We use a simple technique to derive the MST of the proposed protocols, which gives 0.462 and 0.5545 for the first (SICTA/SC) and the second (SICTA/SCC) modification, respectively. In addition to their desirable complexity properties the novel protocols outperform all known conventional TAs (STA and MTA) and the SICTA/SCC has higher MST than that of the notorious FCFS (0.4871).

However, the same SIC technique may be used to modify the FCFS protocol itself. It is known that the similar modifications of the FCFS protocols with single memory location have the MST of 0.6048 and 0.6173, respectively. Despite the fact that the proposed protocols have lower MST, we notice that the practical implementation of the FCFS-based approaches is complicated due to the theoretically infinite precision of the system timer. Therefore, our proposals demonstrate a good balance between implementation complexity and guaranteed performance.

The practical performance of all the protocols that the SIC property is degraded by the imperfect interference cancellation. We extend our system model to account for the cancellation errors and introduce two probabilities. A meaningless signal is obtained after the cancellation of the successful signal with probability q and after the cancellation of the collision signal with probability q'. We notice that the discussed SICTA- and FCFS-based protocols that have the nonzero MST in the infinite population model suffer from a deadlock in the presence of cancellation errors. To improve the robustness of the proposed solutions, we modify SICTA/SCC to make it resistant to cancellation errors for the cost of its MST. The resulting modification (R-SICTA/SCC) has the MST of 0.5147 when $q' = q = 0$, which is still higher than that of the FCFS protocol. In addition, this protocol demonstrates satisfactory MST performance even for the high values of q and q' (see Fig. 6) and even in its worst-case behavior has the guaranteed MTA performance (0.375).

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