Fast Convergence Outer Loop Link Adaptation With Infrequent Updates In Steady State

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***Abstract*—In wireless communications, link adaptation is used to select a suitable modulation and coding scheme. The purpose of link adaptation is to adapt to varying channel and interference conditions and to aim for a specified block error rate or to maximize the throughput. In support of link adaptation, there will be estimates of signal to interference ratios, path gain or transmit powers. These estimates can contain systematic and random errors, that may affect the performance of link adaptation. To correct for such errors, there is an outer loop performing link adaptation, usually based on feedback of the bit error rate. We investigate commonly used outer loop link adaptation algorithms and propose a new scheme based on sequential hypothesis testing. The new scheme is shown to converge faster at initialization and after disturbances and to have good performance in steady state.**

Keywords—outer loop link adaptation, hypothesis testing

I. INTRODUCTION

Link adaptation has and will be widely used in 4G and 5G mobile communications networks to select a suitable modulation and coding scheme (MCS). Several criteria may be used to guide the selection of an MCS, for example, a criterion could be to maximize cell throughput and/or to achieve a given block error rate (BLER). To select an appropriate MCS in the downlink, link adaptation relies on measurements provided by the user equipment (UE), i.e. the mobile. These measurements are known as channel quality indicators (CQIs). The base station uses the reported CQIs to assign an appropriate MCS to each user. In practice, CQI reports may provide inaccurate or biased information. This may be due to delays in CQI reporting, missing CQI reports and other reasons. These CQI inaccuracies affect the performance of link adaptation, which in turn results in suboptimal use of radio resources.

The base station also receives acknowledgments that are submitted by a UE after every transmission. These acknowledgments could be either Automatic Repeat Request (ARQ) or Hybrid ARQ (HARQ). In HARQ for example, a HARQ ACK (ACK for short) is reported when the last transmission is correctly decoded, and a HARQ NACK (NACK for short) is reported if the UE was not able to decode the last transmission. These HARQ acknowledgments are used by an outer loop in link adaptation to compensate for inaccuracies in the CQI reports. This strategy is known as outer loop link adaptation (OLLA), see e.g. [5]. OLLA is usually implemented as a controller that corrects the current SINR estimate, i.e. the controller computes a compensated SINR that is equal to the current SINR estimate minus an outer loop adjustment. The controller for outer loop link adaptation is commonly designed to adjust the estimate of the SINR so that an estimate of the BLER based on the HARQ acknowledgments matches a given BLER target.

In the literature, researchers have focused on providing fast convergence for the classic OLLA strategy. In fact, [1] has shown that the slow convergence of OLLA has a strong impact on the performance of LTE networks. To address this issue, in [2] histograms of previous connections have been used to provide an initial value for the outer loop adjustments to reduce the number of steps needed for the outer loop to reach steady state. In [3] an enhanced OLLA has been proposed. The method proposed in [3] relies on an improved estimate of the instantaneous BLER together with updates of the outer loop adjustment at every transmission time interval (TTI). To improve the speed of the convergence [7] proposes to increase the step size of the OLLA at the beginning of the connection.

In the current paper, a novel algorithm for OLLA is proposed. The strategy considers a controller for OLLA that operates in three modes. The first operation mode aims to compensate for large changes in the SINR inaccuracies. The second operation mode aims to compensate medium size changes in the SINR inaccuracies, and the third operation mode makes no change in the outer loop adjustments for small SINR inaccuracies.

One of the main aspects of the proposed solution is the use of Sequential Hypothesis Testing (SHT) to keep the BLER within a desired range. In fact, SHT is used to implement the second and third operation modes described above. An advantage of the proposed approach is that SHT detects with a minimum number of measurements when the perceived BLER is outside of the desired BLER range. Additionally, the proposed solution requires a low computational complexity.

II. PROBLEM FORMULATION

In this section link adaptation is described. Consider a UE that sends a CQI report to the base station. The base station uses the reported CQI values to generate an estimate of the SINR (in logarithmic units). This SINR estimate denoted as $\hat{\gamma}$ may be inaccurate due to delays and/or a systematic bias in the CQI reports. The aim of the OLLA is to compensate for these SINR inaccuracies by applying an offset, Δ_{OLLA}, to the SINR estimate, i.e. the compensated SINR estimate, $\hat{\gamma}^{comp}$, which is given by the following relationship in the logarithmic domain, [5]

$$\hat{\gamma}^{comp} = \hat{\gamma} - \Delta_{OLLA} \quad (1)$$

The compensated SINR estimate is later used to compute the MCS. The OLLA uses current and past HARQ acknowledgments as inputs and provides as an output the value of the outer loop adjustment, Δ_{OLLA}, that compensates for SINR inaccuracies.

A classic strategy for OLLA is stepping up and stepping down Δ_{OLLA} with every HARQ acknowledgment. Whenever an ACK is received Δ_{OLLA} is stepped down by Δ_{down}. If instead a NACK is received, then Δ_{OLLA} is stepped up by Δ_{up}. Thus, when the m-th HARQ acknowledgement is received Δ_{OLLA} is updated as follows:

$$\Delta_{OLLA,m} = \begin{cases} \Delta_{OLLA,m-1} - \Delta_{down} & , \ if \ ACK \\ \Delta_{OLLA,m-1} + \Delta_{up} & , \ if \ NACK \\ \Delta_{OLLA,m-1} & , \ otherwise. \end{cases}$$

The ratio between the size of the step down and the step up is chosen to be equal to the ratio between the BLER target and one minus the BLER target, i.e.

$$\frac{\Delta_{down}}{\Delta_{up}} = \frac{BlerTarget}{1-BlerTarget}. \quad (2)$$

This classic OLLA strategy achieves the desired BLER target, see e.g. [3].

For OLLA two main features are desired: first OLLA must quickly react to a large change in the SINR inaccuracies. This feature is particularly relevant when a UE has just been connected to a base station. When the OLLA response is slow, a recently connected UE will experience a long transient time in link adaptation that results in an inefficient use of the radio resources. A fast response of the OLLA is also desirable when large changes in the radio channel conditions occur. These large changes affect the performance of link adaptation mainly because of the delays involved in the CQI reporting. The second desirable feature in OLLA is that it should avoid unnecessary perturbations of the current SINR estimate. These features improve the efficiency of the OLLA on the communication between a base station and the UE.

In the classic OLLA strategy, there is a tradeoff between the features described above. This tradeoff is intrinsic in the choice of the step sizes Δ_{up}, and Δ_{down}. When the step sizes are chosen to take large values, OLLA will quickly compensate for a large change in the inaccuracies of the SINR estimate, but this is at cost of having large corrections on the SINR estimate, even when no correction is needed. On the other hand, when the step sizes are chosen to take small values, then the steady state performance will be better. However, this is at cost of having a slow response when a large change in the SINR inaccuracies occurs.

III. Sequential Hypothesis Testing

Sequential Hypothesis Testing (SHT) [6] is a statistical method to compare two competing hypotheses. This hypothesis testing strategy determines which hypothesis is more likely to be true, and this is achieved with a minimum number of observations. This optimal characteristic of SHT will be used later in the paper to keep the BLER within a desired range. This section presents a brief overview of SHT. For a more detailed description of SHT, we refer the interested reader to [6]. In our case, we want the BLER to be in the range $[p_0, p_1]$. We use SHT to evaluate the competing hypothesis:

$$\text{H0: BLER} \leq p_0; \qquad \text{H1: BLER} \geq p_1.$$

These hypotheses have associated risks that are described by the parameters $\propto$ and β. The parameter $\propto$ is the probability of accepting H1 when H0 is true, and β is the probability of accepting H0 when H1 is true. Every time that a HARQ acknowledgement is received, a hypothesis test is performed that has three possible outcomes: (i) accept H0; (ii) accept H1; and (iii) the test is inconclusive.

The statistical test is performed as follows. Associate y_m with the m-th HARQ observation, where $y_m = 1$ if a NACK is received and $y_m = 0$ if an ACK is received. Next, using the values of $\propto$, β, p_0 and p_1 compute A, R and T as follows [6]

$$A = \frac{\ln\left(\frac{\beta}{1-\propto}\right)}{\ln\left(\frac{p_1(1-p_0)}{p_0(1-p_1)}\right)}; \quad R = \frac{\ln\left(\frac{1-\beta}{\propto}\right)}{\ln\left(\frac{p_1(1-p_0)}{p_0(1-p_1)}\right)}; \quad T = \frac{\ln\left(\frac{1-p_0}{1-p_1}\right)}{\ln\left(\frac{p_1(1-p_0)}{p_0(1-p_1)}\right)}.$$

This selection of parameters A, R and T allows us to determinate when the BLER is outside the desired range, and this is detected using a minimum number of observations [6]. Then initialize an SHT helper variable, ξ_m, by setting $\xi_0 = 0$, and with every new sample compute $\xi_m = \xi_{m-1} + y_m - T$.

The test is inconclusive if $A < \xi_m < R$, and further observations may be needed. At the first time that ξ_m does not lie between A and R, the test is terminated. We accept H0 if $\xi_m \leq A$ and accept H1 if $\xi_m \geq R$.

There are more intuitive ways to determine the SHT parameters $\propto$ and β. Let N_{nack} be the minimum number of NACK samples required to accept H1, and let N_{ack} be the minimum number of ACK samples needed to accept H0. We can compute A and R without directly selecting $\propto$ and β, as follows:

$$A = -N_{ack} \cdot T; \qquad R = N_{nack} \cdot (1 - T)$$

In case that we want to select $\alpha = \beta$, we need $A = -R$. A typical configuration selects $N_{nack} = 2$ and $\alpha = \beta$. Note that by setting N_{nack} and N_{ack} to specific values we are implicitly choosing values for $\propto$ and β. The SHT parameter, T, can be interpreted as a BLER target. In fact, if neither p_0 or p_1 is close to 0 or 1, then $T \approx 0.5(p_0 + p_1)$. However, if we assume that $p_0 \approx 0$ and we want to set $T \approx BlerTarget$, by selecting $p_1 \geq BlerTarget$ and computing p_0 as follows

$$p_0 = \frac{p_1}{(1 - p_1)^{(1-1/BlerTarget)}}$$

we obtain that $T \approx BlerTarget$. These values of T, p_0 and p_1 provide a more intuitive interpretation of the SHT parameters.

IV. Proposed approach

One of the main aspects of the proposed solution is the use of SHT to keep the BLER within the desired range. Another aspect of the proposed strategy is the use of three operation modes. The first operation mode aims to quickly compensate for large changes in the SINR inaccuracies. The second operation mode aims to compensate medium size changes in the SINR inaccuracies, and the third operation mode makes no change in the outer loop adjustments for small SINR inaccuracies.

The first operation mode may be implemented using a legacy control strategy. This operation mode is activated only when the perceived BLER is close to either zero or one. The third operation mode is used when the estimated BLER is close to the target, and the second operation mode is used when the estimated BLER is in the intermediate regions.

The second and third operation modes are implemented using a strategy based on SHT. SHT detects, with a minimum number of HARQ acknowledgments, when the perceived BLER is outside of the desired BLER range. Using this feature of SHT, the controller can keep the perceived BLER within the desired BLER range using a reduced number of control actions. In particular, the outer loop controller does not update Δ_{OLLA} whenever the perceived BLER is within the desired BLER range.

The first advantage of a controller based on SHT is that the controller takes control actions less often. This is a consequence of the fact that the controller does not update Δ_{OLLA} whenever the perceived BLER is within the desired BLER range. Taking control action less often is beneficial because it reduces the perturbations introduced by the OLLA in the compensated SINR estimate. This helps to reduce the effects on other control mechanisms involved in the communication between the base station and the UE.

A second advantage of the method comes from the switching between control operation modes. This allows the OLLA to respond to a large change in the SINR inaccuracies, without significantly changing the performance in steady state. All these features improve the performance of the OLLA and result in an appropriate MCS selection. This ultimately leads to a better use of the radio resources.

A. Outer loop link adaptation structure

Fig. 1a shows a signal diagram and the main components of the proposed method. There are two blocks dedicated to analyze HARQ acknowledgments. The first of these blocks is dedicated to SHT. The SHT block uses the HARQ acknowledgments to compute an SHT outcome. The second block is dedicated to use HARQ acknowledgments for BLER estimation purposes. The output of this block is an estimate of the BLER, θ, examples of BLER estimation follows in later section. Next, the SHT outcome, the BLER estimate, and the HARQ acknowledgments are passed to an outer loop controller. This outer loop controller uses this information to compute the outer loop adjustment that compensates for inaccuracies in the SINR estimates.

B. Outer loop controller

Next, we describe the outer loop controller. Fig. 1b shows a diagram of the internal configuration of the outer loop controller. First, the outer loop controller uses the current BLER estimate to choose an appropriate control operation mode. If the current value of the BLER estimate is close to either zero or one, then the first operation mode is selected, and the standard controller is used. In all other operation modes, the SHT controller is used. The standard controller aims to quickly compensate for large changes in the inaccuracies of the SINR estimates. On the other hand, the SHT controller aims to compensate for small and medium size SINR inaccuracies.

The first operation mode of the outer loop controller that aims to compensate for large changes in the SINR inaccuracies is implemented using a classic OLLA controller. In general, the fast controller will only be used whenever the BLER estimate has a value close to either one or zero. A more precise rule for the activation of the fast controller is provided later in this section. Since the fast controller is used only when the BLER estimate takes these extreme values, a controller implementation stepping up and down will behave almost identically to a controller that compensates for the difference between a BLER estimate and a BLER target.

The SHT controller is responsible for implementing the second and third operation modes of the outer loop controller. These operation modes aim to compensate for medium and small size SINR inaccuracies, respectively. The SHT controller takes actions based on the hypothesis test outcomes. Every time an SHT outcome is received, the SHT controller performs one of the following actions:

- When the SHT outcome is inconclusive, the SHT controller takes no action, and Δ_{OLLA} remains the same.
- When the SHT outcome is “accept H0”, the controller steps down Δ_{OLLA} and starts a new hypothesis test by setting $\xi_m = 0$
- When the SHT outcome is “accept H1”, the controller steps up Δ_{OLLA} and starts a new hypothesis test by setting $\xi_m = 0$.

Notice that ξ_m is set to zero each time that Δ_{OLLA} is updated. The size for the steps on the outer loop adjustment are given as follows:

$$\Delta_{down} = c_1 \cdot BlerTarget \cdot N_{ack}$$

$$\Delta_{up} = c_1 \cdot (1 - BlerTarget) \cdot N_{nack}$$

(a) Signal diagram.

(b) Outer loop controller.

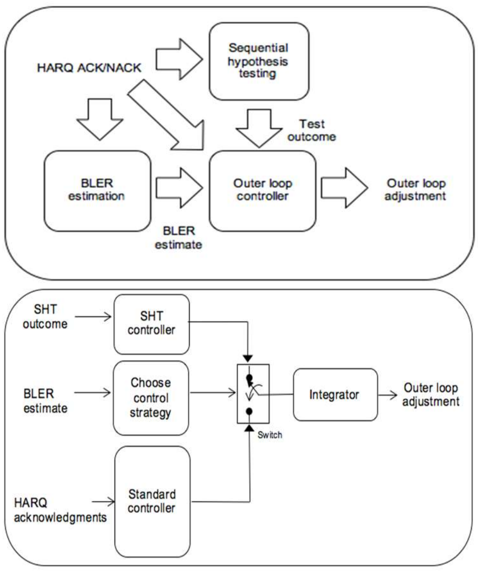

Fig. 1. Proposed method for OLLA.

Here $c_1 > 0$ is a user-supplied parameter, $N_{ack} = -A/T$ and $N_{nack} = R/(1-T)$. The scaling factors N_{ack} and N_{nack} are included to account for the fact that each hypothesis test requires a minimum number of samples before it accepts either H0 or H1. For the user supplied parameter c_1 we recommend that $0 < c_1 < \rho\,(p_1 - p_0)$ where ρ is a constant that approximate the conversion from BLER probability units to SINR in logarithmic units at the operation point. In our simulation we used $\rho = 3$.

A criterion to activate the first operation mode is to test when the BLER estimate is either much less than p_0 or much greater than p_1. The exact threshold value depends on how fast the estimate of the BLER reacts to a large change in the true BLER value. In fact, for an estimator that reacts quickly to a large change in the BLER value, the thresholds to activate the first operation mode may be computed based on an auxiliary variable M_{nack}. This variable counts the number of consecutive NACKs that a BLER estimator requires to move from the $BlerTarget$ to the threshold value that activates the first operation mode. Similarly, we may define $M_{ack} = \frac{M_{nack}(1-BlerTarget)}{BlerTarget}$. For example, if the estimate of the BLER, θ, is computed by filtering the ACK/NACK measurements as follows

$$\theta_m = a\,\theta_{m-1} + (1-a)\,y_m,$$

where a is an auxiliary parameter satisfying that $0 \le a < 1$. Thus, the upper and lower thresholds to activate the first operation mode are given by $(BlerTarget \cdot a^{M_{ack}})$ and $(1 - (1 - BlerTarget) \cdot a^{M_{nack}})$.

One of the advantages of the proposed OLLA approach is its low computational complexity. For each OLLA the storage requirements scale linearly with the number of outer loops. Each outer loop requires storing the following three variables: the value of Δ_{OLLA}, an estimate of the BLER and the value of the internal state of the SHT controller. Moreover, the computational cost of updating the three variables mentioned above scales linearly with the number of outer loops.

Some variants of the proposed method include skipping the use of the BLER estimate to choose the appropriate control strategy in the outer loop controller and using the HARQ acknowledgments instead. Another variant is to choose a different control variable. Instead of controlling the BLER, one may choose to control other variables such as the probability that the transmitted power is within a desired range and the probability that the user throughput is within a desired range.

C. Comparison with previous work

One of the characteristics of the proposed approach is its fast convergence. In the literature, references [3] and [7] have also proposed methods to improve the rate of convergence. These references explored adapting the size of Δ_{down}. In [3] the size of Δ_{down} is dependent on the difference between the instantaneous BLER and the BLER target. Thus, when the difference between the instantaneous BLER and the BLER target takes a given value, the approach [3] uses the same size of Δ_{down}. By contrast, the size of Δ_{down} for the approach in the current paper depends on the controller mode in use. Our approach adds the extra feature of altering the Δ_{down} response depending on which controller is in use, the fast controller or the SHT controller. This additional flexibility in the size of Δ_{down} allows the proposed approach to converge to the BLER target faster than the controller proposed in [3]. In [7] the size of Δ_{down} is increased only at the beginning of the connection. This approach improves the initial convergence rate, but it is not useful when there is a large change in channel conditions.

V. Simulation Results

To illustrate the advantages of the proposed method some simulation results are presented. The proposed OLLA strategy is compared against the classic OLLA strategy. We consider a map with 9 sites and 74 UEs. We assume that half of these UEs are using voice over LTE (VoLTE), i.e. they transmit 1200 bytes every 40ms. The simulations are based on the RUNE simulator [4]. First, we analyze the response of the OLLA to a large change in the conditions. Simulations are 30 seconds long and include a -10dB perturbation in Δ_{OLLA} of the VoLTE users at t=10 seconds.

For all controllers, we take $BlerTarget$ 0.1. For the classic OLLA strategy two configurations are used, one with $\Delta_{down} = 0.01$ and another one with $\Delta_{down} = 0.05$. For the SHT controller, we use $N_{nack} = 2$, $M_{nack} = 3$, $\alpha = \beta$, $c_1 = 0.1$, $p_0 = 0.08$ and $p_1 = 0.12$. The fast controller is implemented with the classic OLLA strategy with $\Delta_{down} = 0.05$.

Fig. 2 shows the evolution of Δ_{OLLA} for a VoLTE user for all OLLA strategies. After the perturbation is introduced at time 10s, the classic OLLA strategy with $\Delta_{down} = 0.05$ quickly compensates for the perturbation, but this is at cost of having large variations on Δ_{OLLA} in steady state. On the other hand, the classic OLLA strategy with $\Delta_{down} = 0.01$ is the slowest to compensate the perturbation. Notice that the proposed OLLA strategy has both, fast response to a large change and small variation in steady state.

Fig. 3a shows the distribution of the BLER across UEs for the scenario perturbed at 10 s. Notice that the classic strategy with $\Delta_{down} = 0.05$ keeps the UEs' BLER close to the $BlerTarget$. However, the classic strategy with $\Delta_{down} = 0.01$ achieves lower BLER because it takes too much time to compensate the large perturbation. The proposed SHT controller keeps the UEs' BLER within the desired BLER range [0.08, 0.12], but the BLER values tend to be larger than the $BlerTarget$. This is caused by the fast controller that pushes the BLER estimate away from zero.

Next, we study the steady state performance of the proposed approach. A 30-second simulation is performed, without the previous perturbation introduced at 10 seconds. Fig. 3b shows

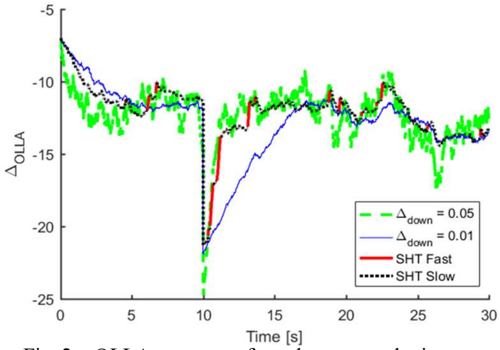

Fig. 2. OLLA response after a large perturbation.

TABLE I. SIMULATION RESULTS

	Average throughput Mbps	% of half-second intervals which BLER is within 0.08 and 0.12.	Percentiles of the delay of packets in buffer [milliseconds]											
			80th	85th	90th	95th	95.5th	96th	96.5th	97th	97.5th	98th	98.5th	99th
Outer loop adjustment is perturbed at 10 seconds														
Proposed strategy	1.948	34.7%	15	16	18	22	22	23	24	26	27	30	33	39
Classic Δ_{down}= 0.01	1.776	33.6%	15	17	19	23	24	24	26	27	29	31	35	40
Classic Δ_{down}= 0.05	1.802	44%	15	17	19	22	23	24	25	27	29	31	35	41
Normal operation														
Proposed strategy	1.961	35.7%	15	16	18	21	22	23	24	26	28	30	33	39
Classic Δ_{down}= 0.01	1.847	36.3%	15	16	18	22	23	24	25	26	28	30	34	39
Classic Δ_{down}= 0.05	1.791	44.5%	15	17	18	22	23	24	25	27	29	31	35	42

the distribution of the average BLER across UEs for this scenario. The classic strategy with $\Delta_{down}= 0.01$ performs better than in the perturbed scenario. The distribution of the BLER for the classic strategy with $\Delta_{down}= 0.05$ is concentrated around the $BlerTarget$. For the proposed strategy the distribution of the BLER across UEs is similar to the previous scenario.

Table I shows statistical results for the scenarios described above. The second column of Table I presents the average uplink throughput. In both scenarios (perturbed and normal operation) the proposed strategy achieves the highest throughput. In the perturbed scenario, the classic strategy with $\Delta_{down}= 0.05$ performs better than when $\Delta_{down}= 0.01$ is used. However, in the normal scenario the classic strategy with $\Delta_{down}= 0.01$ achieves higher throughput than when $\Delta_{down}= 0.05$. The third column of Table I shows the percentage of half-second BLER estimates that lies within the BLER range [0.08, 0.12]. These estimates are computed by observing the ACK/ NACKs for each UE over 0.5 second intervals. The classic strategy with $\Delta_{down}= 0.05$ provides the highest percentage of estimates within the desired BLER range. For the perturbed scenario, the proposed strategy achieves a percentage of BLER estimates within the desired BLER range that is greater than the percentage achieved by the classic strategy with $\Delta_{down}= 0.01$. However, for the normal scenario the classic OLLA strategy with $\Delta_{down}= 0.01$ achieves a percentage that is greater than the percentage achieved by the proposed strategy.

(a) Perturbed

(b) Normal

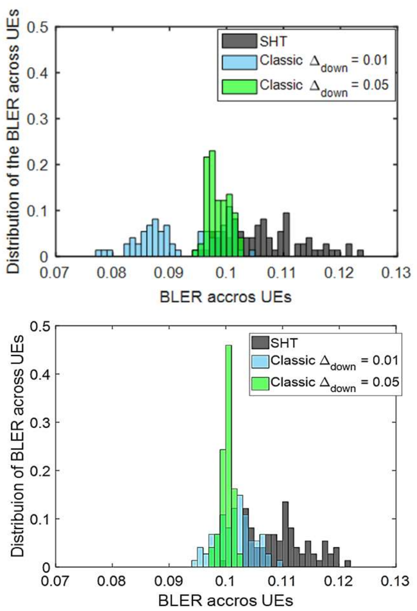

Fig. 3. Distribution of BLER across UEs for the simulated scenarios.

Columns 4 to 15 in Table I show percentiles of the time needed to empty a user's buffer. For the perturbed scenario both classic strategies have similar performance. The proposed strategy is the fastest in emptying the UE's buffers. For the normal scenario, the proposed strategy empties the UEs' buffer faster than the classic OLLA strategies with $\Delta_{down}= 0.05$. In normal operation, the proposed strategy performs similar the classic strategy with $\Delta_{down}= 0.01$.

VI. CONCLUSIONS

This paper has proposed a novel outer loop link adaptation scheme. The scheme achieves two important objectives in the outer loop, namely, fast convergence over transients and good performance in steady state. The proposed scheme addresses these objectives by switching between several operation modes. Fast convergence over transients is addressed by an aggressive control mode, while low outer loop variance in steady state is addressed by a more conservative operation mode with mode selection based on sequential hypothesis testing. Numerical simulations illustrate the efficacy of the proposed scheme.

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