Buffer State Information: Two-Level Water-Filling for Fixed Rate Applications

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***Abstract*—When transmitting at a fixed-rate to a wireless mobile terminal with strict latency requirements channel inversion is often used but at the cost of a significant loss in efficiency. Further, many such systems utilize limited packet buffering at the mobile terminal. In this paper we propose a method to recapture the lost spectral efficiency by exploiting the local buffer. Specifically, in severe channel conditions, latency and buffer state information (BSI) affords the transmitter to wait for good channel conditions rather than attempt to waste power through channel inversion. We propose a scheme that has nearly the spectral efficiency of optimal water-filling in time, yet is able to guarantee Quality of Service by ensuring a probabilistic buffer stability criterion. The solution is a cross-layer approach that utilizes event triggered BSI.**

I. Introduction

Transmission schemes often fall into one of two categories: rate maximization with a power constraint or power minimization with a rate constraint. Each category addresses a different application need and uses a different solution method. Rate maximization addresses best effort oriented traffic and uses a water-filling approach to maximize average spectral efficiency. Transmission only occurs when the channel is sufficiently good. Power minimization is used with fixed rate traffic and uses channel inversion, transmitting at greatest power when the channel is poor. When latency is defined as the time between packet arrival at the transmitter and packet delivery to the application at the receiver, the two categories have different latency characteristics. The latency variation for water-filling can be very large, while it is negligible for channel inversion strategies.

In many practical fixed-rate applications there is a bounded non-zero latency requirement, allowing a buffer to be used to smooth packet delivery to the application. Hence the question arises whether it is possible to attain the spectral efficiency of water-filling by exploiting this buffer while delivering a fixed data rate to the application. An allied question is: can this be done while maintaining buffer stability, i.e. preventing overflow and underflow. In the literature, there are MAC and transport-layer rate-controlling algorithms that ensure a stability criterion at the recipients buffer [1], [2], [3],[4]. However, these algorithms either do not optimize over the PHY-layer information to optimize spectral efficiency, or they do not compare their efficiency to the optimal water-filling solution. In [5], buffer state information (BSI) is utilized to trade additional latency for more throughput, but the focus is on best-effort traffic and not rate-sensitive applications. In [6] and [7], packet-based scheduling is proposed under a dynamic programming framework, rather than a PHY-centric rate and power adaptation scheme.

This paper suggests a scheme that maintains buffer stability and is within a small deviation from the optimal efficiency of water-filling. The new scheme uses a definition of buffer stability as a probabilistic guarantee that the buffer occupancy does not underflow or overflow, as formalized in Section II. Drawing insight from an optimal water-filling scheme, the proposed algorithm is a modified water-filling algorithm with two different water-levels. By utilizing a cross-layer framework that requires both channel and buffer state information (BSI), the new scheme is nearly power-optimal *and* ensures buffer stability.

II. System Model

Consider a user application that requires R_{req} bits every time step from its buffer. Then the buffer occupancy progression is given as,

$$\begin{aligned} b_n &= b_{n-1} + R_n - R_{\text{req}} \\ &= b_0 + \sum_{i=1}^{n} R_i - nR_{\text{req}} \end{aligned} \quad (1)$$

Where R_i is the number of bits that is transmitted and enters the buffer in time step i, and b_0 is the initial buffer occupancy that is assumed to be set via a pre-loading scheme. This paper assumes a non-integer number of bits for tractability when considering water-filling in fading environments.

To guarantee Quality of Service (QoS) to this user, the new scheme considers a failure to occur when either the buffer underflows and the application cannot withdraw bits, or the buffer overflows and packets are dropped. Buffer stability occurs as a probabilistic guarantee that the buffer occupancy b_n does not underflow or overflow at time step n. The worst-case overflow and underflow probabilities are used to establish QoS guarantees.

$$\begin{aligned} &\max_n \text{pr}(b_n \leq 0) \leq \epsilon_1 \\ &\max_n \text{pr}(b_n \geq B_{\max}) \leq \epsilon_2 \end{aligned} \quad (2)$$

In a practical scenario, underflow is more problematic than overflow therefore, in general, $\epsilon_1 \neq \epsilon_2$. However, for clarity and without loss of generality, in the analysis $\epsilon_1 = \epsilon_2 = \epsilon$

The proposed scheme is general to any specific fading model. However, to help develop intuition and provide an example, Rayleigh fading is assumed, and thus the channel power gains are exponentially distributed values.

III. Scheme

The proposed scheme is motivated by a water-filling in time algorithm [8]. Whereas typical water-filling provides a single average rate, $\lambda^{(0)}$ that corresponds to a single water-level $1/\gamma_0^{(0)}$, the new scheme uses a modified water-filling algorithm with two water-levels $1/\gamma_0^{(+)}$ and $1/\gamma_0^{(-)}$. By switching between the different water-levels, the average rate target is either $\lambda^{(+)}$ or $\lambda^{(-)}$ depending on the buffer level. To avoid excessive switching, hysteresis is built into the scheme with two different thresholds B_{L} and B_{H}. At any time instant n, let the transmission scheme provide a water-level that corresponds to the state diagram in Figure 1, and the pictorial representation in Figure 2.

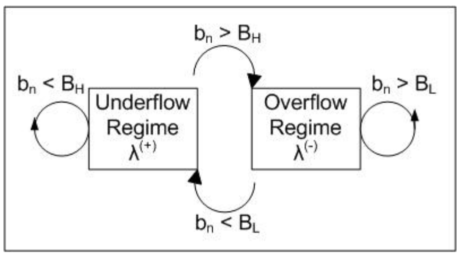

Fig. 1. The average rate target varies between and underflow and overflow regime based on buffer levels.

Consider B_{th} to be the absolute threshold level for underflow and overflow regimes, specifically, the lower threshold $B_{\text{L}} = B_{\text{th}}$ and the high threshold $B_{\text{H}} = B_{\text{max}} - B_{\text{th}}$. The intuition of the scheme is to provide a higher rate target when the instantaneous buffer level falls below a critical threshold to prevent buffer underflow, and similarly for the overflow condition. In general, B_{L} and B_{H} are functions of the physical hardware, and application and delay requirements. Also, as this scheme is a water-filling scheme, channel state information is required at the transmitter.

While the average target rate takes only two values, namely $\lambda^{(+)}$ and $\lambda^{(-)}$, the instantaneous rate is random and based on both the channel and buffer conditions,

$$R_i^{(+/-)} = \begin{cases} \log_2(\gamma_i/\gamma_0^{(+/-)}), & \gamma_i \geq \gamma_0^{(+/-)} \\ 0, & \gamma_i < \gamma_0^{(+/-)} \end{cases} \tag{3}$$

Where $(+/-)$ delineates the buffer level conditions given in Figure 1, i.e. for the same channel state, a high buffer state results in less instantaneous rate than a low buffer state.

IV. Analysis

In this section, the two results are presented:

1. To ensure buffer stability criterion given in Eqn (2), the values of $\lambda^{(+)}$ and $\lambda^{(-)}$ are found.

2. Given the required $\lambda^{(+)}$ and $\lambda^{(-)}$, the corresponding water-levels $1/\gamma_0^{(+)}$ and $1/\gamma_0^{(-)}$ are found, and the power efficiency is compared to optimal water-filling. Namely, as this scheme guarantees buffer stability, its efficiency is not far from water-filling, an optimal power scheme that does not guarantees buffer stability.

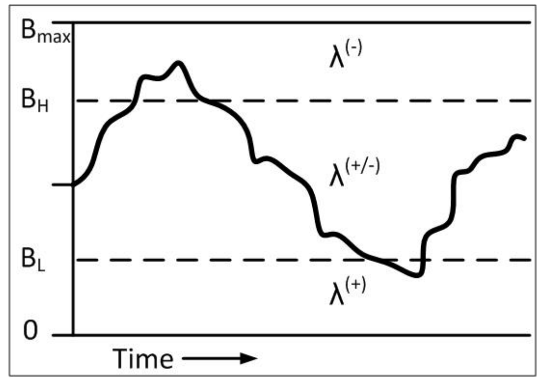

Fig. 2. Proposed scheme uses two different water-levels that correspond to different average rates based on the buffer occupancy.

A. Buffer Stability Criterion

Due to the symmetry of the analysis, this section determines $\lambda^{(+)}$, and a nearly identical analysis can be used to determine $\lambda^{(-)}$. The new method starts with two assumptions: first, the buffer size and threshold are large compared with the application's rate requirement for a given time step:

$$N = B_{\text{th}}/R_{\text{req}} > 10 \tag{4}$$

This assumption is realistic as buffer size is typically much larger than the number of bits an application uses in a scheduling instance. The second assumption is the initial buffer state b_0 can be set through an initial buffer loading transmission scheme (e.g. the user's application does not begin drawing bits until the buffer state crosses the threshold)

$$b_0 = B_{\text{th}} \tag{5}$$

The buffer underflow guarantee is,

$$\begin{aligned} \epsilon &\geq \max_n \text{pr}(b_n \leq 0) \\ &= 1 - \min_n \text{pr}(b_n > 0) \\ &= 1 - \min_n \text{pr}\left(\sum_{i=1}^{n} R_i + B_{\text{th}} - nR_{\text{req}} > 0\right) \end{aligned} \tag{6}$$

From assumptions Eqn (4) and Eqn (5), the buffer cannot go empty in time steps $1, \ldots, N-1$,

$$\text{pr}\left(\sum_{i=1}^{n} R_i + B_{\text{th}} - nR_{\text{req}} > 0\right) = 1,\ n = 1, 2, \ldots, N-1 \tag{7}$$

Therefore,

$$\epsilon \geq 1 - \min_{n:n\geq N} \text{pr}\left(\sum_{i=1}^{n} R_i + B_{\text{th}} - nR_{\text{req}} > 0\right) \tag{8}$$

The worst-case scenario for the underflow regime is that the buffer level does not cross the threshold B_{th} in any of the n steps, hence the R_i's maintain the same statistics and are independent and identically distributed. Further, as $n \geq N > 10$, the Central Limit Theorem approximation is appropriate. Let $X^n = \sum_{i=1}^{n} R_i$, then $X^n \sim \mathcal{N}(n\mathbb{E}[R_i], n\sigma^2_{R_i})$, where the required average rate $\lambda^{(+)} = \mathbb{E}[R_i]$ and $\sigma^2 = \sigma^2_{R_i}$.

Then an expression for underflow probability in terms of $\lambda^{(+)}$ is

$$\begin{aligned}\epsilon &\geq 1 - \min_n \left\{1 - Q\left(\frac{B_{\text{th}} + n\lambda^{(+)} - nR_{\text{req}}}{\sqrt{n}\sigma}\right)\right\} \\ &= \max_n Q\left(\frac{B_{\text{th}} + n\lambda^{(+)} - nR_{\text{req}}}{\sqrt{n}\sigma}\right) \end{aligned} \quad (9)$$

The argument of the Q-function is given as $f(n)$, then using decreasing-monotonicity of the Q-function and convexity of $f(n)$, $\arg\max_n Q(f(n)) = \arg\min_n f(n)$. Therefore,

$$\begin{aligned}N^* &:= \arg\max_n Q\left(\frac{B_{\text{th}} + n\lambda^{(+)} - nR_{\text{req}}}{\sqrt{n}\sigma}\right) \\ &= \arg\min_n \frac{B_{\text{th}} + n\lambda^{(+)} - nR_{\text{req}}}{\sqrt{n}\sigma} \\ &= \frac{B_{\text{th}}}{\lambda^{(+)} - R_{\text{req}}} \end{aligned} \quad (10)$$

And finally, the worst case time step N^* results in a worst case buffer underflow probability,

$$\begin{aligned}\epsilon &\geq Q\left(\frac{B_{\text{th}} + N^*\lambda^{(+)} - N^*R_{\text{req}}}{\sqrt{N^*}\sigma}\right) \\ &= Q\left(\frac{2}{\sigma}\sqrt{B_{\text{th}}(\lambda^{(+)} - R_{\text{req}})}\right) \end{aligned} \quad (11)$$

Within the square root, the first term expresses the buffer threshold's contribution to stability, and the second term expresses how much additional average rate is entering the buffer minus the departure rate.

This leads to the required average rate $\lambda^{(+)}$ that guarantees the worst-case probability of underflow is less than ϵ:

$$\lambda^{(+)} \geq R_{\text{req}} + \frac{\left[\frac{\sigma}{2}Q^{-1}(\epsilon)\right]^2}{B_{\text{th}}} \quad (12)$$

Similarly, the required average rate $\lambda^{(-)}$ that guarantees the worst-case probability of overflow is less than ϵ:

$$\lambda^{(-)} \leq R_{\text{req}} - \frac{\left[\frac{\sigma}{2}Q^{-1}(\epsilon)\right]^2}{B_{\text{th}}} \quad (13)$$

In Figure 3, a Monte-Carlo simulation is given that shows the buffer level progression of the proposed scheme as compared with single level water filling. As is seen, the proposed scheme is able to maintain buffer stability, while single-level water filling is not.

B. Power and Spectral Efficiency

In the previous section, $\lambda^{(+)}$ and $\lambda^{(-)}$ were determined that guarantee buffer stability. This section considers a fixed spectrum allocation (e.g. fixed tone allocation in OFDMA), and considers power optimization through water-filling in time.

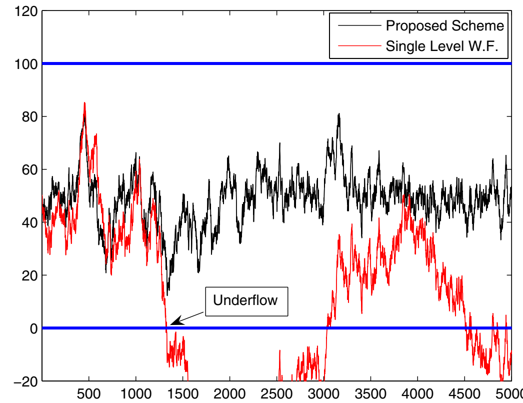

Fig. 3. Proposed scheme maintains buffer stability, while single level water-filling does not.

The power efficiency, and likewise the spectral efficiency, of this scheme derive from the average power needed by this scheme to the optimal water-filling scheme that does not guarantee buffer stability. The general outline of the analysis in this section is:

1. Determine $\gamma_0^{(0)}$ from single-level water-filling, and the $\overline{P^{(0)}}$ required such that $\mathbb{E}[R^{(0)}] = R_{\text{req}}$. It must be restated that, in this case, the average rate equals the required-rate, but there is no guarantee for buffer stability.

2. Determine an expression for $\gamma_0^{(+)}$ and $\gamma_0^{(-)}$ that correspond to $\lambda^{(+)}$ and $\lambda^{(-)}$, respectively.

3. Determine an expression for the average power levels $\overline{P^{(+)}}$ and $\overline{P^{(-)}}$ corresponding to the two water-levels.

4. Determine the proposed scheme's average power level $\overline{P^{\text{BSI}}}$

5. Find the power efficiency multiplier, $\overline{P^{\text{BSI}}} = \eta\overline{P^{(0)}}$

(1) To find $\gamma_0^{(0)}$ and $\overline{P^{(0)}}$, first solve the average rate requirement in terms of $\gamma_0^{(0)}$,

$$\begin{aligned}R_{\text{req}} &= \int_{\gamma_0^{(0)}}^{\infty} \log_2\left(\frac{\gamma}{\gamma_0^{(0)}}\right) p_\gamma(\gamma) d\gamma \\ &= \int_{\gamma_0^{(0)}}^{\infty} \log_2\left(\frac{\gamma}{\gamma_0^{(0)}}\right) \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right) d\gamma \end{aligned} \quad (14)$$

Then the required power $\overline{P^{(0)}}$ is given by,

$$\overline{P^{(0)}} = \int_{\gamma_0^{(0)}}^{\infty} \left(\frac{1}{\gamma_0^{(0)}} - \frac{1}{\gamma}\right) \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right) d\gamma \quad (15)$$

(2) Determine an expression for $\gamma_0^{(+)}$ and $\gamma_0^{(-)}$ that correspond to $\lambda^{(+)}$ and $\lambda^{(-)}$, respectively.

Given $\lambda^{(+)}$ and $\lambda^{(-)}$ are set with equality from Eqn (12) and Eqn (13), then the Gumbel Distribution serves as an effective bound to the rates in Rayleigh fading, and approaches the true values in the high SNR regime [9].

$$\lambda^{(+)} \geq \log_2(\overline{\gamma}) - \gamma^{\text{EM}}\log_2(e) - \log_2(\gamma_0^{(+)}) \tag{16}$$

Where $\gamma^{\text{EM}} \approx .57721$ is the Euler-Mascheroni constant. The standard deviation σ is also bounded by the Gumbel Distribution, $\sigma \leq \sigma_{Gum} = \log_2(e)\frac{\pi}{\sqrt{6}}$. This leads to an expression for $\gamma_0^{(+)}$,

$$\log_2(\gamma_0^{(+)}) \geq -\frac{\left[\frac{\sigma_{Gum}}{2}Q^{-1}(\epsilon)\right]^2}{B_{\text{th}}} - R_{\text{req}} + \log_2(\overline{\gamma}) - \gamma^{\text{EM}}\log_2(e) \tag{17}$$

While a formal proof of the Gumbel Distribution bounds on expectation and variance are not shown, consider an informal argument. The Gumbel Distribution arises as the logarithm of an exponential random variable. The rates assigned from water-filling in Rayleigh fading are either the logarithm of an exponential random variable when above a channel threshold, and 0 below that threshold, such that the random variable is non-negative. Therefore the true expectation will be above the Gumbel approximation as it shares the same positive numbers, but substitutes 0 for the negative numbers. Second, the true variance will be below the Gumbel approximation as the contribution to the variance of the negative random variables is reduced to a single mass at zero. As a numerical check, Figure 4 and Figure 5 are shown to be effective bounds.

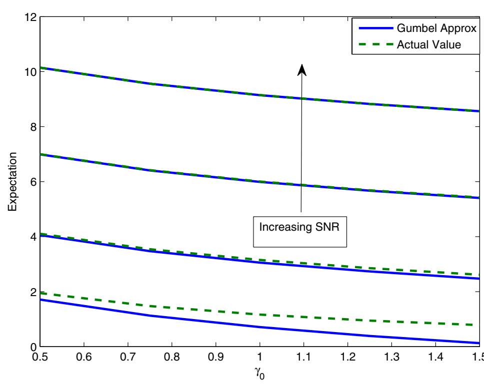

Fig. 4. Gumbel Distribution lower bound of the mean with a SNR from 1dB to 30dB, and 50%-150% of optimal γ_0

(3). Determination of the average powers $\overline{P^{(+)}}$ and $\overline{P^{(-)}}$ for the two different water-levels $1/\gamma_0^{(+)}$ and $1/\gamma_0^{(-)}$, finds upper bounds on a general $\overline{P^{(i)}}$ given some $\gamma_0^{(i)}$ using two ideas: $0 \leq \exp\left(-\gamma_0^{(i)}/\overline{\gamma}\right) \leq 1$ and $\mathbb{E}_{\gamma_0^{(i)}}[1/\gamma] \geq 0$.

$$\begin{aligned}\overline{P^{(i)}} &= \int_{\gamma_0^{(i)}}^{\infty}\left(\frac{1}{\gamma_0^{(i)}} - \frac{1}{\gamma}\right)\frac{1}{\overline{\gamma}}\exp\left(-\frac{\gamma}{\overline{\gamma}}\right)d\gamma \\ &= \frac{1}{\gamma_0^{(i)}}\exp\left(-\frac{\gamma_0^{(i)}}{\overline{\gamma}}\right) - \mathbb{E}_{\gamma_0^{(i)}}\left[\frac{1}{\gamma}\right] \\ &\leq \frac{1}{\gamma_0^{(i)}}\end{aligned} \tag{18}$$

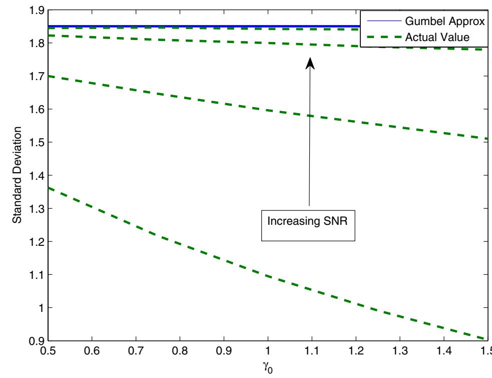

Fig. 5. Gumbel Distribution upper bound of the standard deviation with a SNR from 1dB to 30dB, and 50%-150% of optimal γ_0

4. To determine $\overline{P^{\text{BSI}}}$, steady-state arguments are used to evaluate the fraction of time α spent in the underflow regime, and $1-\alpha$ in the overflow regime.

To determine α, the long-term rates must satisfy R_{req},

$$\begin{aligned}R_{\text{req}} &= \alpha\lambda^{(+)} + (1-\alpha)\lambda^{(-)} \\ \implies \alpha &= \frac{R_{\text{req}} - \lambda^{(-)}}{\lambda^{(+)} - \lambda^{(-)}}\end{aligned} \tag{19}$$

Since $\lambda^{(+)} = R_{\text{req}} + \Delta R$ and $\lambda^{(-)} = R_{\text{req}} - \Delta R$, where,

$$\Delta R = \frac{\left[\frac{\sigma_{Gum}}{2}Q^{-1}(\epsilon)\right]^2}{B_{\text{th}}} \tag{20}$$

Then, $\alpha = \frac{1}{2}$ and the total power usage of this scheme is bounded as,

$$\overline{P^{\text{BSI}}} \leq \frac{1}{2}\frac{1}{\gamma_0^{(+)}} + \frac{1}{2}\frac{1}{\gamma_0^{(-)}} \tag{21}$$

(5). Finally, $\overline{P^{\text{BSI}}}$ is compared to the power level $\overline{P^{(0)}}$.

To determine the power inefficiency, we begin with Eqn (21) and apply Eqn (16) at (a). The following expression is an upper-bound to $\overline{P^{\text{BSI}}}$. For notational clarity, let $K = \log_2(\overline{\gamma}) - \gamma^{\text{EM}}\log_2(e)$,

$$\begin{aligned}\overline{P^{\text{BSI}}} &\leq \frac{1}{2}\frac{1}{\gamma_0^{(+)}} + \frac{1}{2}\frac{1}{\gamma_0^{(-)}} \\ &\leq^{(a)} \frac{1}{2}\frac{1}{2^{K-\lambda^{(+)}}} + \frac{1}{2}\frac{1}{2^{K-\lambda^{(-)}}} \\ &= \frac{1}{2}2^{R_{\text{req}}}2^{-K}\left(2^{\Delta R} + 2^{-\Delta R}\right)\end{aligned} \tag{22}$$

Two approximations then show the general behavior of the inefficiency $\eta = \overline{P^{\text{BSI}}}/\overline{P^{(0)}}$, as below. First, the Taylor Series expansion is inserted into (b). Finally, the upper-bound $\overline{P^{(0)}} \leq 2^{R_{\text{req}}}2^{-K}$ approximates $\overline{P^{(0)}}$ in (c), where the upper-bound is found as in Eqn (22). While the expression is only an approximation of the true η, it serves two purposes: first, it provides a simple expression that gives intuition. Second, through numerical results in Section V, it is verified to be accurate over a broad range of values.

$$\eta = \frac{\overline{P^{\text{BSI}}}}{\overline{P^{(0)}}}$$
$$\approx^{(b)} \frac{2^{R_{\text{req}}}2^{-K}}{\overline{P^{(0)}}}\frac{1}{2}\left[1 + (\Delta R)\ln(2) + \frac{(\Delta R \ln(2))^2}{2!} + \right.$$
$$\left. \cdots + 1 + (-\Delta R)\ln(2) + \frac{(-\Delta R\ln(2))^2}{2!}\right]$$
$$= \frac{2^{R_{\text{req}}}2^{-K}}{\overline{P^{(0)}}}\left[1 + \frac{1}{2}(\ln(2))^2(\Delta R)^2\right]$$
$$\approx^{(c)} \left[1 + \frac{1}{2}(\ln(2))^2\left(\frac{\left[\frac{\sigma_{Gum}}{2}Q^{-1}(\epsilon)\right]^2}{B_{\text{th}}}\right)^2\right] \quad (23)$$

Or simply,

$$\overline{P^{\text{BSI}}} \approx \overline{P^{(0)}}\left[1 + \frac{1}{2}\left(\frac{\left[\frac{\sigma_{Gum}}{2}Q^{-1}(\epsilon)\right]^2}{B_{\text{th}}\log_2(e)}\right)^2\right] \quad (24)$$

As is evident in the above analysis, the power inefficiency goes as ΔR^2. Therefore, for reasonable parameter values, the proposed scheme quickly approaches the power efficiency of single-level water-filling. The approximation closely models the true inefficiency as given in Section V.

V. Numerical Results

In this section, the power efficiency and spectral efficiency of the proposed scheme is compared to single-level water-filling and optimal-truncated channel-inversion. Single-level water-filling will provide the optimal efficiency for an average rate requirement but cannot maintain buffer stability. Optimal-truncated channel-inversion is an optimal scheme when a fixed-rate at every time step is required [8], but suffers a significant efficiency penalty to water-filling. Through the simulations, it is shown that the proposed scheme has an efficiency near single-level water-filling *and* maintains buffer stability.

The QoS parameter $\epsilon = 5\times10^{-3}$. The two quantities shown are the normalized power efficiency and the spectral efficiency. Both curves are normalized by the assigned bandwidth, therefore the units are R_{req} $[bps/Hz]$ and B_{th} $[bits/Hz]$. To make comparisons with Shannon capacity, the instantaneous requirement R_{req} was arbitrarily set to the ergodic capacity C, and $N = B_{\text{th}}/R_{\text{req}}$ and $B_{\text{max}} = 2B_{\text{th}}$.

Normalized power efficiency is the average power each scheme requires to maintain an average rate R_{req} normalized by the power required by optimal single-level water-filling. As can be seen, at higher SNRs, channel inversion progressively becomes more suboptimal than water-filling. In comparison, the proposed scheme approaches the power efficiency of single-level water-filling.

The spectral efficiency curves measure the efficiency of a transmission scheme normalized by the allocated bandwidth. Channel-inversion cannot match the spectral efficiency of optimal water-filling, while the proposed scheme does approach the optimal efficiency. In Figure 6 and Figure 7, $N = 10$, the minimum value that satisfies assumption Eqn (4). At higher N, the proposed scheme converges faster to single-level water-filling.

It should also be noted that the approximation given in Eqn (24) is a good approximation over a wide range of parameter values, especially at higher SNRs and $N > 10$.

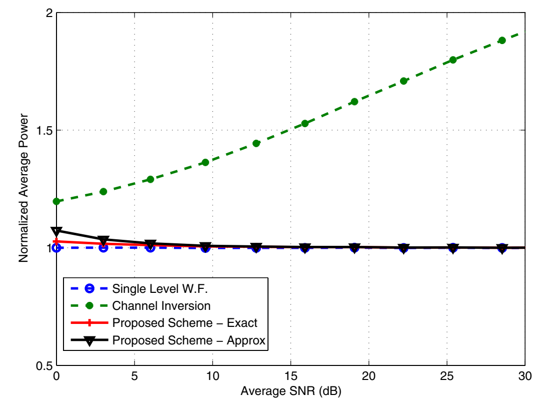

Fig. 6. Normalized power efficiency for $N = 10$.

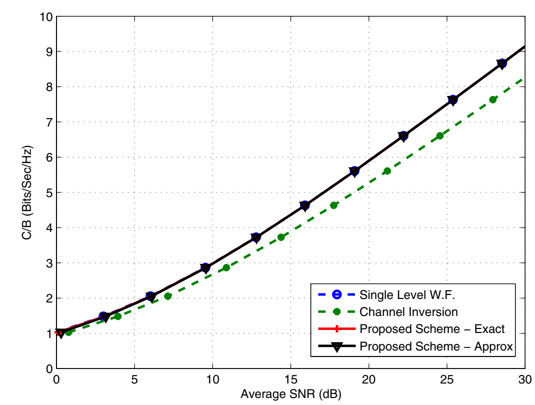

Fig. 7. Spectral efficiency for $N = 10$.

VI. Summary

In this paper, a scheme was proposed that achieves nearly the spectral efficiency of water-filling *and* meets a buffer stability criterion for a fixed-rated objective. By utilizing a cross-layer approach that uses buffer state information, the proposed scheme switches between two different water-levels. This approach allows a control mechanism that ensures that the buffer level at the user does not overflow or underflow, yet is close to the optimal power efficiency of single-level water-filling. Numerical results were presented to validate the analysis.

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