

Channel State Awareness based Transmission Power Adaptation for Efficient TCP Dynamics in Wireless Networks

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Abstract—Although the problem of mal-performance of TCP in wireless scenario has been extensively addressed, an integrated solution has remained undeciphered. Conventionally, measures have been suggested to either adapt or shield TCP from non-congestion losses over the wireless channel. On the other hand, the issues of wireless channel compensation and error control for achieving a better quality channel, have been extensively studied too. Recent efforts to investigate joint approaches [1], [2] do not model TCP dynamics over wireless channel, but study the impact of power control and link layer error correction mechanisms in relation to standard TCP throughput models. In this work, we propose and evaluate transmission power adaptation as integrated solution to mal-performance of TCP in wireless networks. The congestion control dynamics of bulk-transfer TCP flow are modeled for the wireless channel, and an optimization framework is delineated. Based on dynamic programming solutions and low-complexity heuristics, adaptive power control measures are suggested and analyzed for their merit. Via simulations, we demonstrate that suitable power adaptation can lead to a considerable improvement in TCP throughput for slow and fast fading channels.

Index Terms—Wireless Networking, Congestion control, Dynamic Programming, Rayleigh fading, AWGN channel.

I. INTRODUCTION

Innovation in manufacture of portable wireless personal devices has led to a proliferating interest in mobile access to Internet-based applications. Along its evolution and widespread growth, Internet has relied on TCP as its standard transport layer protocol. The integration of mobile devices with the wired-network and network homogeneity are desirable concerns. The deployment of TCP in wireless networks is hence a necessity. Since TCP dynamics and congestion control procedures are tuned for a reliable channel, adaptation to the vagaries wireless environment becomes a challenge. The problem been well researched. Proposed solutions [3], [4], [5] target either TCP awareness and adaptation to non-congestion losses, or incorporation of measures at lower layers to hide such losses from transport layer. The former adaptation measures equip TCP sender with the ability to identify non-congestion losses and not invoke congestion control measures. This however comes at the cost of requirement of change in protocol dynamics and implementation thereof. Other set of solutions hides non congestion losses from the TCP sender, and aims to enhance the link quality as seen by transport layer.

Variability in wireless channel conditions in itself is a challenge. Channel compensation and error correction methods like transmission power and rate adaptation, FEC, have been well investigated and deployed in wireless networks. We note that a unified solution to the mal-performance of a wireless network employing TCP, has remained undeciphered. Recent

attempts [1], [2] target maximization of an objective function which depends on a general TCP throughput expression. The throughput is taken to be a function of average round trip time and TCP segment loss probability. We argue that a throughput expression having dependence on channel conditions only via segment error rate may not completely capture TCP dynamics in relation to channel effects like multipath fading. Some investigative attempts at examining the effects of fading on TCP performance include [6], [7].

Observing the need for an integrated approach, we target channel compensation methods to optimize TCP performance. We propose an approach for cross-layer tunneling across the wireless network stack and investigate transmission power adaptation as a measure to prevent TCP performance degradation in wireless scenario.

This paper is organized as follows. Section II discusses the operational scenario and states the assumptions. In section III, TCP dynamics under different channel conditions and as captured in an optimization framework based on dynamic programming principles, are discussed. The system model for evaluation is outlined in Section IV. A comparison of TCP performance with optimal power adaptation and other power control schemes is presented in Section V. In Section VI, we propose and validate low-complexity heuristics for dynamic programming based power adaptation. The paper is concluded in Section VII.

II. SCENARIO AND ASSUMPTIONS

We consider a steady state bulk transfer TCP flow between a mobile client and an Internet host. Bulk TCP transfer in wireless networks has previously been considered, amongst other works, in [3], [6], [7], [10]. Fig. 1 shows the scenario of focus for our work.

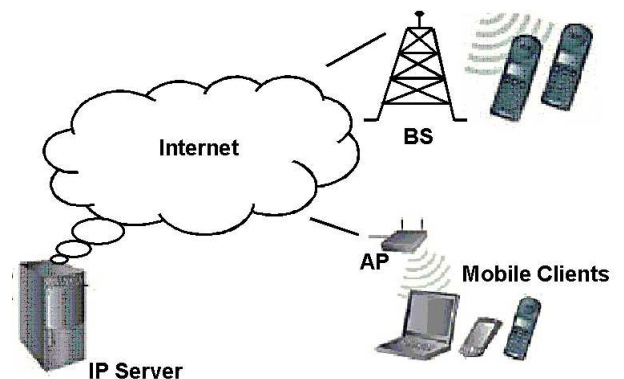


Fig. 1. Scenario for TCP session in a network with wireless hop.

Transmission power is controlled on the uplink or downlink wireless channel depending on the direction of TCP flow between the mobile device and the Base Station (or Access Point). We regard packet losses to be due to channel errors on the wireless hop and congestion related losses are taken to be relatively minimal. This enables us to focus on TCP's performance degradation due to wireless losses. Similar assumption is made in several other works including [3]. Our analysis applies for a given modulation scheme and transmission rate on the wireless hop. Consequently, the Round Trip Time (RTT) of TCP packets does not change due to rate variation. For the scenario where adaptive modulation is used, the optimal power adaptation measures proposed in this work can be evaluated and effected for different modulation schemes.

Link layer error correction methods are not modeled in our work. FEC is widely deployed as link-layer error recovery mechanism. We have observed that bit error rates of as low as 10^{-8} can be required to achieve TCP throughput capacity. FEC methods alone may not be capable of achieving such error rates under all mobility and multipath fading patterns. We, in this work, choose to focus on an integrated approach that solves TCP problems by adapting transmission power in accordance with protocol's evolutionary dynamics. Power control measures are getting increasingly deployed in wireless networks and are crucial because of concerns like interference mitigation and battery power conservation.

For our scenario, ARQ mechanisms at link layer are also discounted, and transmission power for a TCP packet passed on to the lower layers, is adapted to channel conditions. We note that the prevalence of link-layer error correction mechanisms, in addition to the power control proposed in this work, would add on to the TCP's performance benefits.

Several versions of TCP [3], [6], [7], [8], [9] have been analyzed in terms of their performance merit on wireless links. Our objective is to adopt the basic mechanisms of a widely deployed TCP version and suggest a unified approach to optimize TCP performance for wireless scenario. Hence, we, for our work, account for the fast retransmit and timeout mechanism of TCP Reno. Incorporation of any enhancements to TCP would mean additional performance benefits for our scenario.

III. TCP DYNAMICS OVER WIRELESS CHANNEL AND OPTIMAL POWER ADAPTATION MEASURES

In this section we present a framework for TCP performance optimization over wireless channel. Bulk transfer throughput is of interest to us, and congestion avoidance mechanisms are considered for the purpose.

The adopted terminology is similar to that in [11] and [12]. TCP's congestion avoidance behavior is modeled in terms of rounds. A TCP round begins with the back to back transmission of a window of packets and ends on reception of an ACK for one of these packets. The window size undergoes an additive increase, in case a round of packets is successful. Packet loss can be detected either by reception at TCP sender of triple-duplicate acknowledgements (four ACKs with the same sequence number) or via timeouts. The former event

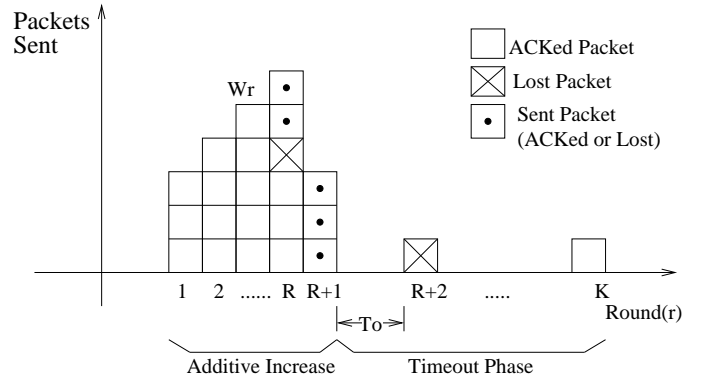


Fig. 2. Packet transmission dynamics during a TCP cycle.

is called Triple Duplicate (TD) loss indication and the latter a Timeout (TO) indication. A Triple Duplicate Period (TDP) is defined as the period between two successive triple duplicate loss indications.

A sample path of evolution of TCP congestion window size is sketched in Fig. 2. Transmission of a window of W packets commences a round, where W is the size of congestion window. Each ACK increases the window size by $1/W$, so that the window size is $W + 1$ for the next round. It is assumed here that the number of packets, b , acknowledged by a received ACK is 1. Two phases are shown in the figure: the additive increase phase and the timeout phase. Consider the case when a packet is lost in the current round. A timeout phase follows, if, amongst the packets in the current round and the next round that are transmitted following the lost packet, any less than three are successful. The TCP timeout value is denoted by T_0 in the figure and the timeout durations double with every unsuccessful attempt. For the ease of reference, we denote by the term *cycle*, the period between the beginnings of two successive additive increase phases. In the event of a timeout loss indication, a cycle ends at round K as shown in the figure and the window size evolves from 1 for the next cycle. In the event that the loss in round R generates a TD indication (three packets following the lost packet are successful and generate duplicate ACKs), the cycle terminates at round $R + 1$. The window size is then reduced to half, and the additive increase for the next cycle follows.

We next address the problem of finding transmission power levels that optimize TCP throughput for wireless channel. Our goal is to maximize the throughput achieved, while keeping the cost of transmission power minimum. The trade-off between TCP throughput and power cost is captured in a dynamic programming framework. While modeling the framework for TCP dynamics, we realized that equations for long term horizon involving countably infinite TCP cycles are beset with excessive dimensionality limitation. We hence adopt an approach whereby we focus on a TCP cycle and make the termination cost of the cycle favor termination with a large window size. This, in addition to inherent dependence between cycles due to window size dynamics of TCP, enables us to reduce the system states and obtain sub-optimal solutions.

Our methodology involves controlling the packet success probabilities to minimize transmission power cost and maxi-

mize the throughput. We denote by g , the channel gain factor. It is related to channel Signal to Noise Ratio (SNR) γ as $\gamma = g\bar{P}/N$, where \bar{P} is the average transmission power and N is the noise power. For a constant noise power, the channel gain is directly proportional to SNR. We consider, in the following subsections, two different cases of channel variation patterns.

A. Slow Channel Variations

We assume for this scenario that the channel decorrelates over RTT intervals and all the packets in a round experience the same channel condition. These packets are hence targeted to have the same success probability, s . Transmission power is a function of packet success probability and channel gain for the round, and is denoted by $P(s, g)$. The channel gain and success probability being constant for a round, P remains constant too. With W_r representing the congestion window size in round r , the expected cost to-go from round r , can be formulated as

$$J(r) = \int_g \min_s \{W_r P(s, g) + s^{W_r} J(r+1) + (1 - s^{W_r}) C_{Loss}(r)\} f_g(g) dg \quad (1)$$

$W_r P(s, g)$ represents the cost attributed to power used for transmitting packets in current round r . $J(r+1)$ in the above equation, is the cost-to-go from round $r+1$, conditioned on all packets being successful in current round. $C_{Loss}(r)$ represents the cost that will be incurred after round r , conditioned on the occurrence of one or more packet losses. Given the success probability for this round, the packet success process is independent, and hence the probability of the entire round being successful is s^{W_r} .

We next discuss the formulation of $C_{Loss}(r)$. In the event of packet loss in a round, a TD or TO indication results. First consider the case when the packet loss results in TD indication. Let $p_{TD}(r)$ be the probability that a triple duplicate loss indication is generated for a lost packet in round r , given that one or more packet losses have occurred in round r . For this case we note that the round $r+1$ is the last round of this cycle, since packet loss is inferred in round $r+1$ and a new cycle begins thereafter. The transmission power cost for the last round is denoted by $C_L(r)$ and the termination cost in the event of TD loss indication is denoted by $C_B(r)$. Next consider the case when a TO indication occurs. The event has a probability $1 - p_{TD}(r)$, conditioned on the occurrence of at least one loss in the round. Then, $T(r+1, r)$ represents the cost-to-go from the beginning of timeout period.

The cost $C_{Loss}(r)$ in (1) can now be expressed as

$$C_{Loss}(r) = p_{TD}(r)(C_L(r) + C_B(r)) + (1 - p_{TD}(r))T(r+1, r) \quad (2)$$

We next derive the probability $p_{TD}(r)$. In the event of packet loss in round r , triple duplicate indication occurs if 3 or more packets are successful amongst $W_r - 1$ packets transmitted after the lost packet. Clearly $p_{TD}(r)$ is not only a function of r , but depends on the packet success probability

of the next round as well. We approximate the latter success probability as the current round's success probability s . Then,

$$p_{TD}(r) = \sum_{i=3}^{W_r-1} \binom{W_r-1}{i} s^i (1-s)^{W_r-1-i} \quad (3)$$

$T(k, r)$ represents the cost to go from round k for the timeout period starting after round r and can be expressed as

$$T(k, r) = \int_g \min_s \{P(s, g) + s C_{TO}(k, r) + (1-s)T(k+1, r)\} f_g(g) dg \quad (4)$$

(4) has structural similarity with (1). $C_{TO}(k, r)$ represents the terminal cost associated with the end of timeout sequence. The timeout sequence ends when packet transmission is successful with probability s .

It remains to discuss the terminal costs in (2) and (4). We regard $C_B(r)$ and $C_{TO}(r)$ to be composed of two elements. The first component is the negative of throughput achieved when the current cycle terminates at round r . Thus, higher the throughput, greater the cost deduction from the cycle cost. The second component $-\rho(W_r)$ is introduced to influence the dynamic programming evolution of the current cycle to favor high throughput in the following cycle. For a large W_r , the next cycle would have a large initial window size, and thus would yield more throughput. To favor that, cost for current cycle should have a higher cost deduction when the cycle terminates at a high W_r . Thus $\rho(W_r)$ should be increasing in W_r . We choose $\rho(W_r) = \frac{W_r}{2}$.

For the TD loss indication case the termination cost is given by

$$C_B(r) = \lambda \left(-\frac{\sum_{i=1}^r W_i + n_l}{(r+1)RTT} - \rho(W_r) \right); \quad (5)$$

where n_l is the expected number of packets transmitted in the round following the one where the loss occurred. For the ease of analysis, we assume n_l to be $\frac{W_r}{2}$ where W_r is the window size of the round where one or more packet losses have occurred. Similar assumption is made in [12]. λ is the cost ratio scaling factor between the power and throughput costs.

In the event of timeout, the terminal cost $C_{TO}(k, r)$ is given by

$$C_{TO}(k, r) = \lambda \left(-\frac{\sum_{i=1}^r W_i + n_l + (k-r)}{(r)RTT + f(k)T_0} - \rho(W_r) \right); \quad (6)$$

where $f(k)$ denotes the timeout sequence given by

$$f(k) = \begin{cases} 2^{k-r} - 1, & k - r \leq 7 \\ 127 + 64(k - r - 7), & k - r \geq 8 \end{cases} \quad (7)$$

We define round R_t to be the final round of the additive increase phase of the TCP session. R_t is selected large enough such that any given TCP period ends before this round number, with sufficiently high probability. With a fixed terminal round, the dynamic programming equation (1) is finite-period and its

solution can be obtained. For the solutions presented later in this paper, R_t is selected based on simulation observations. Similarly we define K_t to be the terminal round of the timeout evolution (4).

B. Fast Channel Variations

In this case, we assume that the channel decorrelates over packet transmission duration. Thus packets in the same round will experience different channel conditions. We denote by vector \vec{g} , the channel gains for packets in a round. The parameter to be optimized is \vec{s} , the probability of successful transmission of all the packet in the round.

$$J(r) = \int_{\vec{g}} \min_{\vec{s}} \left\{ \sum_{w=1}^{W_r} P(s_w, g_w) + \left(\prod_{w=1}^{W_r} s_w \right) J(r+1) \right. \\ \left. + (1 - \prod_{w=1}^{W_r} s_w) C_{Loss}(r) \right\} f_{\vec{g}}(\vec{g}) d\vec{g} \quad (8)$$

For the evaluation of optimal success probability vector \vec{s} in equation (8), the complete channel gain vector \vec{g} for the current round is required. However, for a real scenario, the knowledge of channel condition for all the packet in a round is not possible apriori. In light of this, we modify the formulation to yield an approximate cost model that is causal, and can be solved. We first select the targeted packet success probability to be the same for all packets in the round. Then \vec{s} simplifies to a single-element optimization parameter s . Having no information about the channel gains for the packets in the round, we replace the power cost of each packet in (8) by power consumption averaged over the channel gain distribution, $\int_g p(s, g) f_g(g) dg$. The cost formulation $J(r)$, with no apriori knowledge of the channel gain vector, then becomes

$$J(r) = \min_s \left\{ W_r \int_g P(s, g) f_g(g) dg + s^{W_r} J(r+1) \right. \\ \left. + (1 - s^{W_r}) C_{Loss}(r) \right\} \quad (9)$$

The formulation of $C_{Loss}(r)$ can be explained as the slow channel variation case. The cost structure for the timeout phase is as expressed by (4). The approximate formulation above is found to yield considerable performance enhancement as shown in the later discussion on solutions. (9) and (4) are made finite-period as in the slow channel variation case.

IV. SYSTEM MODEL AND POWER CONTROL SCHEMES

Having modeled TCP dynamics and considered optimization techniques for different underlying wireless channel conditions, we proceed to delineate a framework to evaluate TCP throughput. We present the system model for assessment and introduce some standard power control schemes.

We target power adaptation to achieve fading compensation, and issues of multi-user interference mitigation and path loss compensation are not addressed. The wireless channel is taken to be flat-fading, with AWGN Rayleigh fading model. The wireless link is assumed to be high-bandwidth so that it does

not pose a limitation to realizable TCP throughput. For the purpose of evaluation, we choose BPSK to be the modulation scheme. As mentioned before, power adaptation measures proposed in this work can be evaluated and adopted for different modulation schemes and transmission rates.

The channel state is represented by SNR γ , observed on the channel without any transmission power adaptation. Since the noise and interference power is taken to be constant, the channel gain g follows a Rayleigh distribution, as does γ . We assume that constant length TCP packets are encapsulated in physical frames and there is no segmentation. There is no error correction coding and hence a TCP packet is in error if any of the bits of the encapsulating frame is in error [15]. Furthermore we assume that error detection mechanisms are capable of identifying bit errors incurred during transmission. Given the SNRs for constituent bits in the frame, the bit loss is an independent process. Hence for a frame length of N bits, the packet error probability p and bit error probabilities $p_{b,i}$'s can be related as

$$p(\gamma_1, \dots, \gamma_N) = 1 - \prod_{i=1}^N (1 - p_b(\gamma_i)) \quad (10)$$

where γ_i is the SNR for bit i . For an AWGN channel and BPSK modulation, the bit error probability is

$$p_b(\gamma) = Q(\sqrt{2\gamma}) \quad (11)$$

where Q denotes the Q-function and the SNR γ follows the exponential distribution with mean $\bar{\gamma}$ as per the Rayleigh fading channel assumption.

$$f_{\gamma}(\gamma) = \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right), \gamma \geq 0 \quad (12)$$

Our objective is to model a reasonably simplified wireless channel and investigate the impact of power control measures on TCP throughput.

We now refer to the power control policies that shall be employed and TCP throughput behavior be assessed therewith. $P(\gamma)$ refers to the transmission power as a function of SNR γ . γ is the observed SNR if the average power \bar{P} is used for transmission on the channel. All power control policies are subject to the average power constraint

$$\int_{\gamma} \frac{P(\gamma)}{\bar{P}} d\gamma = 1 \quad (13)$$

Following are the power control measures that shall be adopted.

- **No Power Adaptation:** The transmission power in this case remains constant and is equal to the average power. In other words, no power adaptation to channel conditions is done.

$$\frac{P(\gamma)}{\bar{P}} = 1 \quad (14)$$

- **Truncated Channel Inversion:** Truncated Channel Inversion (TCI) power adaptation [14] attempts to compensate for fading over a cut off fade-depth. It attempts to maintain a constant received SNR. The power adaptation for a lower cut-off SNR γ_c is given by

$$\frac{P(\gamma)}{P} = \begin{cases} \frac{\sigma}{\gamma} & \gamma \geq \gamma_c \\ 0 & \gamma < \gamma_c \end{cases} \quad (15)$$

where σ is the constant received SNR, which, subject to the constraint 13, given by

$$\sigma = \frac{1}{\int_{\gamma_c}^{\infty} \frac{1}{\gamma} f_{\gamma}(\gamma) d\gamma} \quad (16)$$

- **Water-filling Power Adaptation:** The transmission power to average power relation for water-filling [14] power control is given by

$$\frac{P(\gamma)}{P} = \begin{cases} \frac{1}{\gamma_0} - \frac{1}{\gamma} & \gamma \geq \gamma_0 \\ 0 & \gamma < \gamma_0 \end{cases} \quad (17)$$

where γ_0 is the lower cut-off SNR and can be evaluated from the constraint (13) on transmission power. The power adaptation policies dictates transmission at a high power when the channel is good, and at low power when the channel is bad.

For the described system model and power adaptation measures, the adopted parameter values are shown in Table I.

| Parameter | Value |
|------------|------------|
| b | 1 |
| T_0 | 3 s |
| γ_c | 5 dB |
| N | 1500 bytes |
| RTT | 250 ms |
| W_{max} | 48 |

TABLE I
PARAMETER VALUES FOR TCP THROUGHPUT ASSESSMENT.

The number of packets, b , acknowledged by a received ACK is 1, the timeout value T_0 is 3s and cut-off γ_c for TCI is taken to be 5dB. N , the length of a TCP packet encapsulated in a physical frame, is taken to be 1500 bytes. A value of 250ms is chosen for average RTT. It reasonably represents, for instance, a scenario with a TCP session having a wireless end-hop and the complete session extending over large wireline network. The maximum window size for TCP, W_{max} is taken to be 48.

V. TCP THROUGHPUT EVALUATION

With the system model presented in the previous section, we proceed to evaluate TCP throughput under varying channel conditions and with different power adaptation schemes.

We simulate bulk transfer of TCP packets in a scenario highlighted in Section II. TCP sender in the wireless network is saturated, i.e., has data to send all times. Success probability of a TCP packet is ascertained by the state of the wireless hop of the connection and transmission power level on the link. Channel gain experienced by the a frame encapsulating TCP packet is ascertained based on the fading distribution and the channel model presented Section IV. The transmission power levels are selected depending on the power adaptation policy. The Rayleigh fading channel is taken to have an exponentially

distributed gain g with an average value 1. For simulations, we discretize the gain values to 500 levels.

The approach for evaluating TCP throughput with power adaptation based on dynamic programming solutions, is discussed next. We first consider the slow fading case. Equations (1) and (4) are converted to finite-period via measures indicated in Section III-A. The terminal round values R_t and K_t are each taken as 200. The channel gains and success probabilities are discretized. The following procedures are performed for a range of values of the cost ratio λ . For every round number r , a look up table comprising of success probability s , as a function of channel gain g is generated. This evaluation is done for the additive increase and timeout phases. Note that for a given round number and a channel gain, the value s that minimizes the integrands in (1) (and likewise (4)) is the success probability stored in the look up table. For the simulation run, the channel gain value is drawn every round from a Rayleigh distribution. The success probability for that round is then retrieved from the look-up table. Knowing the channel gain and success probability value, the transmission power for packets in that round is determined. Throughput is evaluated by determining the number of packets transmitted during the simulation run. Several runs are performed to obtain an average throughput value.

With increasing values of λ , the priority given to throughput cost in the dynamic programming formulation increases relative to the power cost. Hence increasing throughput values are obtained, but at the cost of higher average power. The throughput variation based on DP solutions is shown in Fig. 4. Recall that the average power is proportional to average SNR.

Fig. 4 also shows TCP throughput based on other power adaptation measures. These results are obtained as described next. For a given value of average SNR, $\bar{\gamma}$, the parameters σ and γ_0 can be evaluated respectively for TCI and water-filling power adaptation. While σ can be evaluated from (16), γ_0 can be determined from (13) and (17). During a simulation run for a given value of $\bar{\gamma}$, as the channel gains are drawn from a Rayleigh distribution, the corresponding SNRs are determined from the relation $\gamma = g\bar{\gamma}$. The transmission powers can then be ascertained from power control measures (15) and (17). For no power adaptation, the transmission power level remains equal to the average power. Again, the average power is proportional to the average SNR.

It can be seen from Fig. 4, that a considerable throughput benefit is obtained via DP based power control, for the shown SNR range. Throughput improvement of as much as around 10 times over that with no power control, is effected by adapting the power suitably. While TCI based power control improves TCP throughput, water-filling power adaptation does not display any merit.

We next discuss the fast fading case, for which we evaluate solutions to (9) and (4). The approach followed is similar to that for slow fading case above. However, the solution in this case results in a single value of s for a given round, irrespective of the gain value. Recall that (9) is an approximation to the optimization formulation (8). Due to causality concerns, a constant success probability is targeted for all the packets in

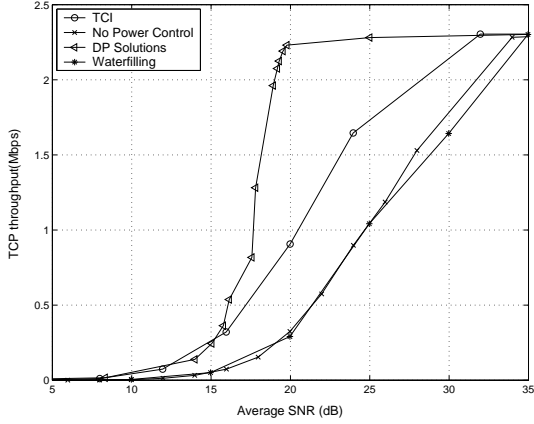


Fig. 3. TCP throughput for slow fading case.

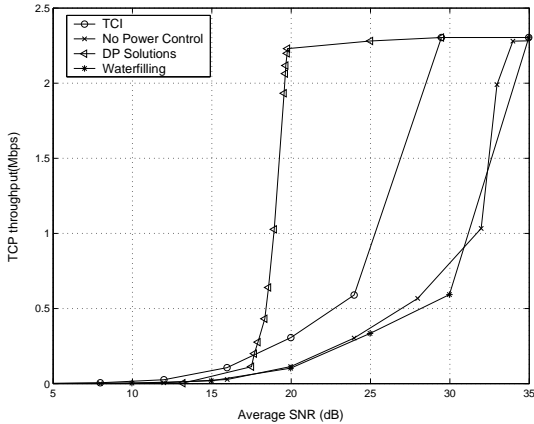


Fig. 4. TCP throughput for fast fading case.

a round. The transmission power cost for packets is taken be an average over the channel gain distribution and hence the DP solution for s is not a function of gain. For performing simulations, channel gain is selected for each packet from the fading distribution. The success probability for the current round is noted from the fast-fading DP look-up table and the transmission power is ascertained. Fig. 3 shows TCP throughput for resulting power adaptation as compared to other power control schemes. Substantial throughput gains are observed for SNR range shown in the figure. Again, it can be observed that the throughput is improved by as much as around 10 times as compared to TCP throughput with no power adaptation. TCI and water-filling power control show the same pattern of variation as the slow fading case.

VI. HEURISTIC DESIGN

We have demonstrated that dynamic programming based power adaptation can bring about substantial TCP throughput benefits for wireless channel. However, the computation of DP solutions in a real scenario may be beset with processing power limitations. We, in this section, present heuristics that obviate the necessity for computation of DP solutions. The approach involves an analytical function design to approximate the optimal packet success probability generated via DP solutions. The required transmission power for a given channel

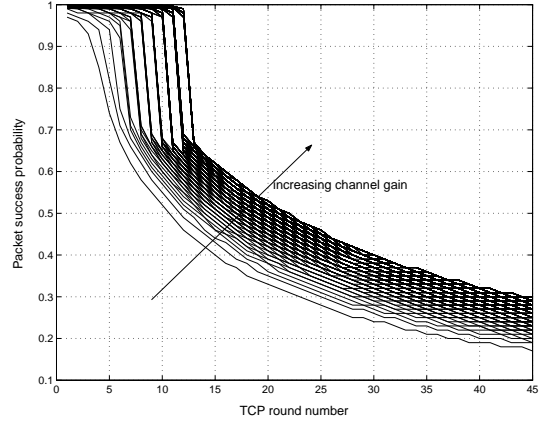


Fig. 5. Optimal probability of successful transmission in additive increase phase.

gain and TCP round can then be ascertained by the transmitter without the need for DP computation. We discuss the heuristic design for slow and fast fading cases, adopting the system model presented in Section V.

We first consider the slow fading case. Fig. 5 plots the packet success probability s for different channel gains, as evaluated by solving (1) and (4) for a fixed cost ratio. We observe several traits useful for heuristic design: a) s is decreasing with TCP round number r for a given channel gain value. This is because the early rounds are more important for the overall system throughput and need to be protected against packet loss via high power and thus high packet success probability b) s is increasing with channel g for a given round r . This is intuitive as well: as the channel conditions improve, high packet success probability can be maintained. In addition to the above, we have observed the following from DP results: c) for a given g and r , s increases with the cost ratio λ d) For channel gain below a threshold g_{th} , the packet success probability is close to zero (curves for such channel gain are not visible in Fig. 5), and e) for fixed g and r , the threshold g_{th} decreases with λ .

With these observations, we design our heuristics as follows. The truncation threshold g_{th} is approximated by $g_0 f(\lambda)$, where $f(\lambda)$ is a decreasing function, and converges to 1 as $\lambda \rightarrow \infty$. Hence for values of channel gain lower than the threshold, the success probability is taken to be 0. For $g \geq g_{th}$, the target success probability s for round number r and channel gain g is modeled as,

$$s(r, g) = \min\{s_{max}, \beta \exp((R_t + 1 - r)^{1/\lambda} - R_t^{1/\lambda})(1 - Q(\sqrt{g}))\}$$

where s_{max} is the maximum value of s and β is $1.5s_{max}$. Q is the Q-function and is used here to capture the effect of channel gains on packet success probability. R_t is the terminal round number, as defined in Section III-A.

DP solutions for timeout phase are computationally expensive. We observe that by fixing the power levels for timeout phase to be the power for the first round of TCP cycle, the deviation from optimal throughput is insignificant. We make this choice of power levels for the solutions based on heuristics

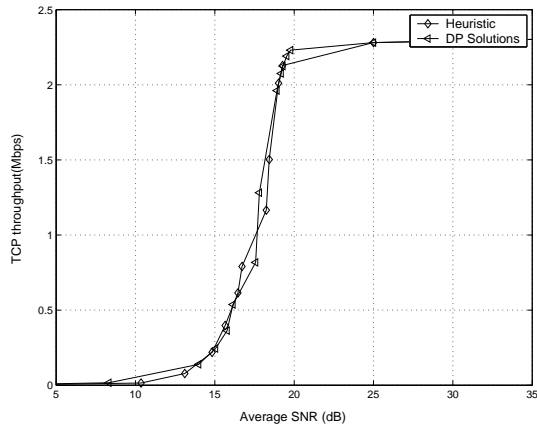


Fig. 6. Comparison between TCP throughput obtained via dynamic programming solutions and heuristics, for slow fading case. $R_t = 200$, $g_0 = .0045$, $s_{max} = 0.9999$ and $f(\lambda) = (\lambda + 4)/\lambda$.

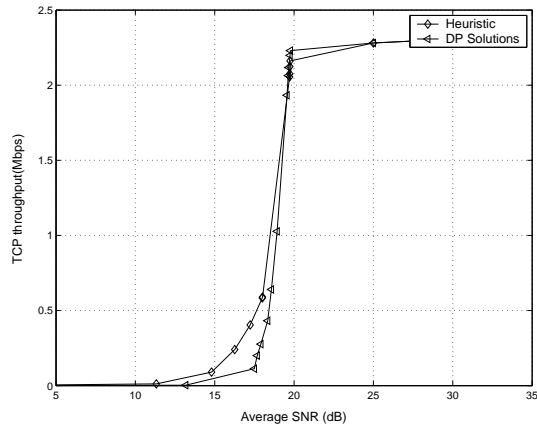


Fig. 7. Comparison between TCP throughput obtained via dynamic programming solutions and heuristics, for fast fading case. $R_t = 200$, $g_0 = .0045$, $s_{max} = 0.9999$ and $f(\lambda) = (\lambda + 4)/\lambda$.

as well as DP. Fig. 6 compares the TCP throughput based on heuristic-based model for a given set of parameter values, with DP solutions based throughput.

We next consider the fast fading case. Recall that (9) is an approximation to the optimization formulation (8). Due to causality constraints, same success probability is maintained for each packet in the round. Furthermore, this target success probability is not a function of channel gain. The success probability is thus modeled as,

$$s(r) = \min\{s_{max}, \beta \exp((R_t + 1 - r)^{1/\lambda} - R_t^{1/\lambda})\};$$

where threshold g_{th} is given as before and $s(r)$ is 0 for $g < g_{th}$. Fig. 7 shows the comparison of the model for a given set of parameters, with actual throughput results.

It can be seen that the throughput based on the heuristics, closely approximates the throughput based on DP solutions.

VII. CONCLUSION

We, in this work, develop a framework for modeling and optimizing TCP dynamics for wireless scenario. As solutions to dynamic programming equations, we evaluate opti-

mal power adaptation measures. We perform simulations to demonstrate the resulting throughput improvement. To obviate computationally complex DP solution procedures, heuristics for power adaptation are presented. We conclude that dynamic power adaptation can be employed as an integrated solution to counter the degradation suffered by TCP under varying wireless channel conditions.

We are currently looking at modeling approaches to incorporate link-layer error correction mechanisms. We are also exploring mechanisms to tunnel TCP round number information to a BS/AP exercising DP heuristics-based power adaptation. Note that in the event of TCP bulk transfer from an Internet host to a mobile client, power is controlled by the BS/AP and the heuristic-based power adaptation requires knowledge of TCP sender's round numbers in addition to channel gains.

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