Identifying almost sorted permutations from TCP buffer dynamics

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Mathematics Subject Classifications:
68R05 (Discrete mathematics in relation to computer science; Combinatorics),
68M12 (Computer system organization; Network Protocols)

Abstract

Associate to each sequence $A$ of integers (intending to represent packet IDs) a sequence of positive integers of the same length $M(A)$. The $i$'th entry of $M(A)$ is the size (at time $i$) of the smallest buffer needed to hold out-of-order packets, where space is accounted for un-received packets as well. Call two sequences $A, B$ equivalent (written $A \equiv_{FB} B$) if $M(A) = M(B)$.

We prove the following result: any two permutations $A, B$ of the same length with $SUS(A), SUS(B) \leq 3$ (where SUS is the shuffled-up-sequences reordering measure [3]), and such that $A \equiv_{FB} B$ are identical.

The result (which is no longer valid if we replace the upper bound 3 by 4) was motivated by RESTORED, a receiver-oriented model of network traffic we introduced in [7].

Keywords: TCP, packet reordering, shuffled up sequences.

*This work has been supported by PN-II “Parteneriate” Grant 10028/14.09.2007 from Romanian CNCSIS.
1 Introduction

The TCP protocol \cite{15} is the fundamental protocol for computer communications. TCP breaks the information into packets, and attempts to maintain an ordered packet sequence to be passed to the application layer. It accomplishes this by buffering packets that arrive out-of-order.

Recent work in the area of network traffic modeling has brought to attention the significant impact of packet reordering on the dynamics of this protocol \cite{1, 2, 10}. This has stimulated research (mainly applied, rather than mathematical) on measuring and modeling reordering \cite{14, 12}, and on quantifying the impact of packet reordering on application performance.

In this paper we study a combinatorial problem motivated by modeling packet reordering in large TCP traces: suppose that we map a sequence $A$ of packet IDs into the sequence of integers $M(A)$ representing the different sizes of the buffer space necessary to store the out-of-order packets; we assume that space in the buffer is reserved (and accounted) for unreceived out-of-order packets as well. What kind of additional information on the sequence $A$ is needed to uniquely identify $A$ given $M(A)$?

The problem arose in the context of RESTORED \cite{7}, a method for receiver-oriented modeling and compression of large TCP traces. Previously we showed experimentally \cite{7} that RESTORED is able to regenerate sequences similar to the original sequences with respect to several reordering metrics. One of these metrics was the reorder density (RD) from \cite{14, 8, 13}. For RD the experimental result is somewhat counterintuitive since

1. RESTORED generates sequence that are (locally) similar (with respect to mapping $M$ to the original sequence).

2. RD can take different values on sequences that map to the same sequence via $M$.

Because of this latter property, the fact that the reconstructed sequences have similar properties with respect to the original sequence does not follow from the theoretical guarantee 1).

The result in this paper, together with the experimental observation that over 99% of the traces we previously considered for benchmarking RESTORED obey the constraint present in our result, explains why the theoretical inconsistence of RD is not observed in the “real-world” data we employed to benchmark RESTORED.
2 Preliminaries

We first give a brief primer on the relevant aspect of the TCP protocol, RESTORED and the concepts used in the sequel.

The TCP protocol [15] attempts to maintain an ordered stream of data bytes, identified by an integer called byte ID, that is effectively communicated through the network by breaking it down into packets. The ordering is maintained by buffering out-of-order packets. The dynamics of the buffer can be described in part using several parameters.

1. The first parameter is $\text{NextByteExpected}$, and is the smallest index of a data byte that has still not been received by the receiver.

2. A second, related, parameter is $\text{LastByteRead}$, the index of the last byte processed by the receiver-side application that communicates through the network via the TCP protocol. Throughout this paper we will make the simplifying assumption that data is read by the application as soon as it is ready. In other words $\text{NextByteExpected} = \text{LastByteRead} + 1$.

3. Another parameter is $\text{LastByteRcvd}$, the index of the last byte that has arrived at the receiver, awaiting processing.

4. $\text{RcvWindow}$, the size of the receiver window, is a receiver-maintained parameter that is meant to provide the sender an estimate of the available buffer space at the receiver.

5. Finally, $\text{RcvBuffer}$ is a implementation-dependent system constant, the size of the receiving buffer.

The functioning of the TCP protocol ensures that these four parameters are related through the relation ([9] section 3.5):

$$\text{RcvWindow} = \text{RcvBuffer} - [\text{LastByteRcvd} - \text{LastByteRead}]$$  (1)

The term in parantheses on the right-hand side is the actual size of the TCP receiver-buffer. The measurement takes into account space reserved (but not necessarily used) for all packets from the first expected to the last arrived. This is, of course, proportional to the buffer size measured in packets rather than bytes if it is the case that all packets have the same size.
TCP is receiver-driven: that is, the receiver attempts to maintain control on the sender flow stream by directing the sender speed, and acknowledging the received packets. An acknowledgment (shortly, ACK) generally consists of the ID of the first packet that has not yet been received. Acknowledgement mechanisms vary from implementation to implementation, and can entail delayed or selective acknowledgments, urgent retransmission requests, etc. From our standpoint, what is important that we can associate a sequence of integer ACKs to every sequence of packet IDs, the sequence of ACKs that would be sent if the receiver would immediately acknowledge every packet received.

Example 1 Consider the following hypothetical sequence of packet IDs: \( A = (4 \ 3 \ 2 \ 1) \). Then the sequence of ACKS is \( \text{ACK}(A) = (1 \ 1 \ 1 \ 5) \).

Restored \cite{7} is Markovian model of large TCP traces that incorporates information on the dynamics of packet reordering. It can be used to provide estimates of various measures of quality of service without making these measurements online, or storing the entire sequence. Rather, it first “compresses” the trace into a small “sketch” that allows regeneration of a TCP trace with (hopefully) similar characteristics. If needed, we can then perform a large number of measurements on the regenerated trace.

For the purposes of the present paper, a connection is simply a sequence of integers (packet IDs). Suppose that the receiver observes the following (hypothetical) packet stream

1 2 3 6 5 7 4 8 9 10 12 13 14 11.

In this example packets with IDs 4, 5, 6, 7, 12, 13, 14 and 11 arrive out of order. One can, consequently, classify the received packets into two categories: those that can be immediately passed to the application layer, and those that have to be temporarily stored before delivery. In the example, packets 5, 6, and 7 are temporarily buffered, and the buffer is only flushed when packet 4 is received. Similarly, packets 12, 13, and 14 are temporarily buffered, and the buffer is flushed when packet 11 arrives. We will call a packet that marks the end of a sequence of consecutively buffered packets a pivot packet. Packets that are immediately delivered to the application layer are also trivially pivots. In our example this is the case for packets 1, 2, 3, 4, 8, 9, 10 and 11.
The distinction we introduced effectively defines a coarsened representation of the stream of packet IDs using two states: an ordered state $\mathcal{O}$, in which packets arrive when they were supposed to, and an unordered state $\mathcal{U}$ in which there is reordering and buffering. Each occurrence of State $\mathcal{O}$ is followed by one or more occurrences of State $\mathcal{U}$.

The dynamics of packet IDs in the ordered state is trivial by definition: in order, starting with the first expected packets. In [7] we dealt with the dynamics of packet IDs in the unordered state, and defined a many-to-one mapping $\mathcal{M}$, sending sequences of IDs into “sketches.”

**Definition 1** Let $A = \{A_1, A_2, \ldots, A_n\}$ be a sequence of packet IDs. We define the $\mathcal{M}$ as an operator that after receiving a packet $A_i$ at time index $i$, outputs the difference between the highest ID ($H_i$) seen so far and the highest ID ($L_i$) that could be uploaded.

$$\mathcal{M}(A_i) = H_i - L_i.$$  \hfill (2)

In other words, $\mathcal{M}$ is the size of the smallest buffer large enough to store all packets that arrive out-of-order, where the definition of size accounts for reserving space for unreceived packets with intermediate IDs as well. The buffer sequence $\mathcal{M}(P)$ associated with a sequence $P$ of packet IDs is simply a time-series of $\mathcal{M}$ values.

Two sequences of packet IDs $P$ and $Q$ are full buffer (FB) equivalent (written $P \equiv_{\text{FB}} Q$) if $\mathcal{M}(P) = \mathcal{M}(Q)$.

**Example 2** Let $A = (4 \ 3 \ 2 \ 1)$. Then $\mathcal{M}(A) = (4 \ 4 \ 4 \ 0)$.

The mapping $\mathcal{M}$ is many-to-one, but an inverse can be computed in polynomial time [6]. This was used in the regeneration algorithm, where in the unordered state we first sample a sketch $S$ from the distribution of such sketches and then reconstruct a sequence of IDs that maps (via $\mathcal{M}$) to $S$.

Mapping $\mathcal{M}$ provides a formal way to guarantee that the reconstructed sequences are locally “similar” to the original one. The formal notion of similarity has implication for the dynamics of the TCP protocol:

**Definition 2** Two packet sequences $A, B$ are behaviorally equivalent if they yield the same sequence of ACKs.
Suppose now that a TCP implementation uses simple ACKs (as opposed to SACK), and acknowledges every single packet then \(\textit{two sequences that map (via } \mathcal{M} \text{) to the same sequence are behaviorally equivalent} [4].\) As the dynamics of the congestion window is receiver-driven, assuming identical network conditions for the two ACK sequences, the two traces can be regarded as “equivalent,” from a receiver-oriented standpoint.

We will also need a standard measure of disorder [3]. This measure is denoted by shuffled up-sequences (SUS) and is defined as follows:

**Definition 3** Given sequence of integers \(A\) denote by \(\text{SUS}(A)\) the minimum number of ascending subsequences into which we can partition \(A\).

For example, a sequence \(A = \langle 6, 5, 8, 7, 10, 9, 12, 11, 4, 3, 2 \rangle\) has

\[
\text{SUS}(A) = ||\{\langle 6, 8, 10, 12 \rangle, \langle 5, 7, 9, 11 \rangle, \langle 4 \rangle, \langle 3 \rangle, \langle 2 \rangle\}|| = 5, \tag{3}
\]

where \(||S||\) denotes the cardinality of a set \(S\).

## 3 Main result

In this section we will prove our main result:

**Theorem 1** Let \(A, B\) be permutations of length \(n\) with \(\text{SUS}(A), \text{SUS}(B) \leq 3\) such that \(A \equiv_{FB} B\). Then \(A = B\).

**Observation 1** The theorem is no longer true if we replace the condition with \(\text{SUS}(A), \text{SUS}(B) \leq 4\). This is witnessed by sequences \((4 \ 3 \ 2 \ 1)\) and \((4 \ 2 \ 3 \ 1)\). Indeed \(A \equiv_{FB} B\), since they both map to sequence \((4 \ 4 \ 4 \ 0)\). In fact \(\text{SUS}(A) = 4, \text{SUS}(B) = 3\).

**Proof.** We consider the greedy algorithm for computing SUS displayed in Figure[1]. The algorithm has been implicitly proved correct in [11]; the reason is parameter SUS was shown to be equal to another presortedness measure denoted by LDS, and defined as follows:

**Definition 4** Let \(A = (a_1, a_2, \ldots, a_n)\) be a sequence of nonnegative integers. \(\text{LDS}(A)\) is defined as the longest length of a decreasing subsequence \(a_{i_1} > a_{i_2} > \ldots a_{i_j} \ (1 \leq i_1 < i_2 < \ldots < i_j \leq n)\) of \(A\).
Algorithm SUSGreedy(W)

**INPUT:** a list $W = (p_1, p_2, \ldots, p_n)$ of non-negative integers.

```
let $i = 1$;
let $j = 1$;
let $L_1$ be the empty list;
while ($i \leq n$){
    add $p_i$ to the first list $L_t$, $1 \leq t \leq j$
    where it can be added while maintaining it sorted;
    if this is not possible
    {
        $j$++;
        create new list $L_j = \{p_i\}$;
    }
    $i$++;
}
```

let $u$ be the number of lists created by the algorithm;

**OUTPUT** $u = LDS(W) = SUS(W)$.

Figure 1: Greedy Algorithm for computing SUS
With this definition it is easy to see that Algorithm 1 computes parameter LDS (to make the paper self-contained we reprove this result below).

We now give a simple algorithm, displayed in Figure 2, that, given a sequence \( W \) of positive integers constructs (if possible) a permutation \( A \) of size \( n \) with \( \text{SUS}(A) \leq 3 \) such that \( \mathcal{M}(A) = W \). The proof that the algorithm is correct will imply the uniqueness of sequence \( A \).

We prove the correctness of algorithm RECONSTRUCT in a couple of intermediate steps. The first two apply to a general sequence \( A \) (rather than one with \( \text{SUS}(A) \leq 3 \)).

**Proposition 1** Suppose there exists a permutation \( \pi \) with \( \mathcal{M}(\pi) = w \). Then the following are true at any stage \( i \geq 1 \):

1. For any \( j \geq 1 \), the last element added to list \( L_j \) is the maximum element in lists \( L_k \), \( k \geq j \). In particular the largest element of \( L_1 \) is the maximum element seen so far.

2. If element \( x \) is the largest element seen up to stage \( i \) then \( x = \text{ACK}_i + \mathcal{M}_i - 1 \).

**Proof.** Let \( i = 1 \). Statement 1. is clearly true. For the second statement, note that \( \text{ACK}_1 = 2 \) and \( \mathcal{M}_1 = 0 \) if \( x = 1 \) (in-order packet) otherwise \( \text{ACK}_1 = 1, \mathcal{M}_1 = x \).

Consider now the case \( i > 1 \). By the induction statement, the largest element seen so far (call it \( y \)) is the last element of \( L_1 \) and \( y = \text{ACK}_{i-1} + \mathcal{M}_{i-1} \).

**Case 1:** \( x \) is added to \( L_1 \). By the definition \( x > y \) so \( x \) is the largest element seen so far. Moreover, since \( x \) is an out-of-order element we have \( \text{ACK}_i = \text{ACK}_{i-1} \) and \( \mathcal{M}_i = \mathcal{M}_{i-1} + x - y \).

**Case 2:** \( x \) is added to some other list \( L_j \). If \( x \) is the first element of the new list then statement 1 follows immediately. Otherwise let \( z \) be the largest element of list \( L_j \) before adding \( x \). Applying the induction hypothesis it follows that \( z \) is the largest element in lists \( L_k \), \( k \geq j \). But \( z < x \) (since we add \( x \) to list \( L_j \)). Thus \( x \) becomes the new largest element of lists \( L_k, k \geq j \).

As for the second statement, from the algorithm it follows that \( x < y \) so \( y \) is still the largest element seen so far. If the buffer size does not modify then the desired relation follows from \( y = \text{ACK}_{i-1} + \mathcal{M}_{i-1} \) (which holds by induction) and relations \( \text{ACK}_i = \text{ACK}_{i-1} + \mathcal{M}_{i-1} \) and \( \mathcal{M}_i = \mathcal{M}_{i-1} \). Otherwise the
Algorithm RECONSTRUCT

INPUT: a list $W = (w_1, w_2, \ldots, w_n)$ of positive integers.

let PACKET and ACK be integer vectors of size $n$;
with all fields initially equal to $-1$;
let $LARGEST = 0$;
conventionally define $ACK[0] = 0$;
for ($i = 1$ to $n$) {
  if ($w_i < w_{i-1}$) {
    PACKET[$i$] = ACK[$i - 1$];
    ACK[$i$] := ACK[$i - 1$] + ($w_i - 1 - w_i$);
  } else {
    ACK[$i$] = ACK[$i - 1$];
    if ($w_i < w_{i-1}$)
      LARGEST := PACKET[$i$] := LARGEST + ($w_i - w_i$);
  }
}
for ($i = 1$ to $n$) {
  if ($w_i = w_{i-1}$)
    let PACKET[$i$] be the smallest positive integer not present among values PACKET[$j$], $1 \leq j < i$;
}
if (vector PACKET is a permutation of $\{1, \ldots, n\}$)
  return PACKET;
else
  return NO PERMUTATION EXISTS;

Figure 2: Algorithm for reconstructing permutations from buffer sizes
buffer shrinks with size $ACK_i - ACK_{i-1}$, so $M_{i-1} - M_i = ACK_i - ACK_{i-1}$.
We infer the fact that

$$y = ACK_{i-1} + M_{i-1} - 1 = ACK_i - (ACK_i - ACK_{i-1}) + M_{i-1} - 1 =$$

$$= ACK_i + (M_i - M_{i-1}) + M_{i-1} - 1 = ACK_i + M_i - 1.$$

\[\square\]

**Corollary 3.1** Algorithm SUSGreedy correctly computes $u = LDS(A)$ (which is equal \[\Box\] to SUS(A)).

**Proof.** Let $B = a_{i_1} > a_{i_2} > \ldots > a_{i_{LDS(A)}}$ be a decreasing subsequence of $W$ of maximum length, and let $L_1, L_2, \ldots, L_j$ be the lists created by the algorithm on input sequence $A$. Each list $L_k$ is increasing, so it contains at most one element from $B$. Therefore $u \geq LDS(A)$. On the other hand, each element $a_m$ set by the algorithm to a list $L_k$, $k \geq 2$ is smaller than some element $a_n$, $n < m$, set by the algorithm to line $k - 1$ (otherwise $a_m$ would be set to a list $L_j$, $j < k$). Applying this observation starting with the last element of list $L_u$ we create a decreasing sequence of length $u$. It follows that $u \leq LDS(A)$, thus $u = LDS(A)$. \[\square\]

From now on we assume that there exists a permutation $A$ with $SUS(A) \leq 3$ such that $M(A) = w$. We will run the algorithm SUSgreedy along algorithm RECONSTRUCT. First we give a simple corollary of Lemma \[\Box\]

**Corollary 3.2** Suppose that $w_i > w_{i-1}$. Let $y$ be the largest ID of a packet received in stages 1 to $i - 1$ and $x$ be the ID of the new packet. Then

$$x = y + (w_i - w_{i-1})$$

and $x$ is added by SUSgreedy to list $L_1$.

Next we deal with another possible case, the one when the buffer size shrinks:
**Proposition 2**  
(a). Let packet ID $x$ be added at stage $i$, and assume that $w_i < w_{i-1}$ Then $x = \text{ACK}_{i-1}$ and all packets with indices at most $\text{ACK}_{i-1} + (w_{i-1} - w_i - 1)$ have been received in the first $i$ stages.

(b). Suppose packet ID $x$ is added by algorithm SUSgreedy to list $L_3$. Then packet $x$ falls into case (a) of this lemma.

**Proof.**

(a). The fact that $x = \text{ACK}_{i-1}$ follows from the definition of parameter $\text{ACK}$ and the fact that the buffer shrinks. The second relation follows from the fact that the buffer shrinks by exactly $w_{i-1} - w_i$.

(b). Since $x$ goes in list $L_3$, at the time when added $x$ is smaller than the last element in lists $L_1$ and $L_2$. If $x$ were larger than $\text{ACK}_{i-1}$ then the packet with index $\text{ACK}_{i-1}$ (which arrives sometimes after $x$ does) could not be placed in lists $L_1$, $L_2$ or $L_3$, making the sequence $A$ require $\text{SUS}(A) \geq 4$, a contradiction.

The other two relations follow from the definition of parameter $\text{ACK}_i$.

\[ \square \]

Finally, the correctness of the algorithm RECONSTRUCT (and the proof of Theorem 1) follows easily: the correctness of the first for loop in algorithm RECONSTRUCT follows from Corollary 3.2 and Proposition 2. Moreover, if a packet ID $x$ is set at stage $i$ in the second for loop then it must correspond to adding $x$ to list $L_2$. Since list $L_2$ is sorted, $x$ is the smallest element that has not been set up to this stage.

Assuming that permutation $A$ in the preimage of $w$ exists then algorithm RECONSTRUCT is going to output exactly $A$. Since $A$ was chosen in an arbitrary manner, the uniqueness of $A$ follows.

\[ \square \]

### 4 Application to RESTORED

The result we just proved allows the reinterpretation of results in [7, 5]. In that paper it was shown experimentally that RESTORED is able to recover
several measures of quality of service, among them the following metric [8]. For simplicity our version of the metric is adapted to the case of permutations (i.e. sequences with no repeats or packet losses):

**Definition 5 Reorder Density (RD).**

Consider an implementation-dependent parameter $DT$ that is a positive integer or $\infty$. Given a permutation $\pi$ we define the reorder density of $\pi$ as the distribution of displacements $\pi[i] - i$, restricted to those displacements in the range $[-DT, DT]$.

We also need the following definition from [5]:

**Definition 6** A metric $M$ is consistent with respect to $\equiv_{FB}$ if for any two ID sequences $A$ and $B$,

$$A \equiv_{FB} B \Rightarrow M(A) = M(B).$$

In other words, a consistent measure $M$ takes equal values on equivalent sequences.

**Example 3** By equation (7), every measure defined in terms of the time series of parameter $RcwWindow$ (e.g. the average value of this parameter) is consistent with respect to $\equiv_{FB}$.

In particular, since RESTORED (in the form used in [7, 5]) guarantees that, on sequence $A$ it will reconstruct a sequence $R(A)$ such that $R(A) \equiv_{FB} A$, it is not really that surprising that RESTORED should be able to capture any metric consistent with respect to $\equiv_{FB}$. The reason that the experimental results from [7] were somewhat surprising is that RD is an example of an inconsistent measure according to the terminology of Definition 6.

**Observation 2** If $A = (4\ 3\ 2\ 1)$ and $B = (4\ 2\ 3\ 1)$ then the distributions of displacements are $D(A) = \begin{pmatrix} -3 & -1 & 1 & 3 \\ 1/4 & 1/4 & 1/4 & 1/4 \end{pmatrix}$ and $D(B) = \begin{pmatrix} -3 & 0 & 3 \\ 1/4 & 1/4 \end{pmatrix}$, respectively. It is easy to see that, no matter how we set the parameter $DT$ to either a positive integer or $\infty$, the truncated versions of distributions $D(A), D(B)$ are going to be different. Thus $A \equiv_{FB} B$ but $D(A) \neq D(B)$, which means that measure RD is inconsistent independently of the value of threshold parameter $DT$.  

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However, Theorem 1 forces us to reevaluate this statement: since the vast majority of traces used in [7] had $SUS \leq 3$ the measure is "consistent in practice" (at least on this dataset). Theorem 1 also exposes a weakness of the encoding used in [7]: on "real-life" traces the extra potential compression given by the many-to-one nature of map $FB$ is not present.

5 Acknowledgments

I thank Anders Hansson for useful discussions.

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