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Estimating Data Transfer Capacity for Intermittent Connectivity: A Transport Aware Model

Johan Garcia, Stefan Alfredsson, Anna Brunstrom

Department of Mathematics and Computer Science

Karlstad University, Sweden

Email: {johan.garcia, stefan.alfredsson, anna.brunstrom}@kau.se

Abstract—Communication performed with mobile devices will experience varying levels of connectivity as the communication device moves in and out of coverage. A subset of mobile communication devices operate under conditions where the connectivity is characterized by relatively short contact periods occurring intermittently. In this paper we propose a model to predict the amount of data that can be transferred during such short contact periods. The model includes aspects of the transport layer slow-start behavior and is validated using data from a long-running measurement campaign in the networks of four Swedish cellular networks. Further validation of the modeling assumptions is performed by employing a numerical optimization technique based on non-linear least squares regression using the iterative Levenberg-Marquardt approach. The model is then used to explore the relevant parameter space.

Index Terms—Cellular networks, Short contacts, HSPA, LTE, 4G, TCP

I. INTRODUCTION

Communication from mobile platforms are becoming more prevalent. The communication needs of these mobile platforms vary according to their context and intended usage scenario. In some cases the mobile platform is a router with multiple cellular modems that forward traffic coming from WLAN-connected passengers on board a vehicle, such as a bus or a train. In other cases the communication needs come from vehicle internal systems unrelated to passenger communication. Examples of such cases include vehicle telemetry, or transfer of other data sets collected by the vehicle such as video from surveillance cameras. As the vehicles are moving, their level of connectivity varies over time. Depending on the connection technique used, the connectivity may be present for longer periods (such as public transport in a city using 3.5G or 4G networks), or more intermittently (WLAN access points placed at some bus stops along a bus route, or cellular networks in rural areas).

Another context where intermittent connectivity is prevalent is for personal devices when these are communicating opportunistically over short-range technologies such as Bluetooth. In this work we consider a model that is applicable to all circumstances where the communication is intermittent and communication can take place when a communicating node come into coverage of the communication technology used.

In addition to a considerable variation in the link technology contexts of intermittent communications, there is also a large variation in the application-coupled aspects of the intermittent connectivity. In some cases the challenge is to transmit

relatively large amounts of data in the most time-efficient way. When larger amounts of data is to be transmitted, it can be beneficial to have the ability to schedule the transmission of data according to particular constraints. These constraints can be over user-experienced delay in order to optimize the perceived quality of some connection using delay-tolerant or opportunistic communication. Another constraint can be to select the most energy efficient mode of communication from a multi-interface device, possibly with additional constraints.

An additional use case may be predictive activity scheduling. For example, if the communication is done in order to fill up a local cache in a vehicle in preparation for a lack of service, a prediction of the amount of data that can be fetched into the cache can be useful for deciding which content to request.

In this paper we present a model to compute the amount of data that can be transferred over intermittent connectivity, with a focus on short contact times. Data collected from cellular networks were employed to illustrate the validity of the model, and to explore model fitting approaches. The model can also be useful when examining transport protocol efficiency for opportunistic or other intermittent communication, and we present a mapping of a large parameter space for 1 to 10 second contact times.

The remainder of this paper is organized as follows. In Section II related work is discussed. Section III then presents the proposed model for short contact data transfers. The verification of the model is discussed in Section IV. Some insights resulting from using the model are provided in Section V, followed by the conclusions in Section VI.

II. RELATED WORK

Predictions of the data transferred during a contact opportunity can be useful in several domains. The design and performance of delay tolerant networks [5] or opportunistic networks [17] are directly dependent on the contact time that can be expected for the system. Modeling and simulation work in the area is indeed also often based on contact traces gathered at various events such as the Rollernet data set [20] gathered at a roller skating tour or the data set collected at the Infocom 2005 conference [10]. Both data sets were captured using Bluetooth contact loggers. The contact times measured in the Roller net data set ranged from 3.7s to 78.5s. Contact times measured at Infocom 2005 ranged

from the order of seconds to the order of hours. Contact times measured in drive-thru Internet scenarios, where vehicles communicate with roadside access points over WLAN are typically around one minute [14], [8]. As is clear from the above examples, observed contact times can vary greatly and are heavily dependent on the particular network and mobility scenario. Limitations of relying on contact traces is pointed out in [18], which show that contact-based simulations overestimates transfer ratios and underestimates delays, due to for instance not considering limited transmission bandwidths. Models such as the one developed in this paper can be useful complements in this context. When contact times are short, protocol overheads can become significant.

The presented model predicts how much data can be transferred over TCP during a contact opportunity. A similar problem is addressed by Tan et al. [19]. They focus on how much data can be downloaded to a vehicle over 802.11b during a contact opportunity in a drive-thru Internet scenario, where vehicles communicate with roadside access points. Their analysis is based on Markov reward processes and is focused on the MAC layer. It takes things like AP transmission range, contention from other vehicles and speed into account. The reverse problem of how long it takes to transfer a TCP flow of a given size has also previously been studied in the literature. The first modeling of TCP latency was presented by Cardwell et al. in [2], where they extended the traditional throughput model [15] to consider connection setup and TCP slow-start. Lee et al. [11] examine a model that includes a varying TCP initial window size. Garcia et al. [6] present a similar model and use it to study protocol efficiency in cellular networks from an end-user perspective. Protocol efficiency is also studied by Liu et al. [12]. They quantify the aggregate loss in cellular network capacity that occurs as a result of TCP's inability to fully utilize all the available bandwidth. Huang et al. [9] study the efficiency of TCP in 4G networks. Based on a passive bandwidth estimation technique they conclude that the studied TCP connections take on average 52.9% longer to complete than they would have if the bandwidth was fully utilized. Paul et al. [16] study radio resource usage in 3G networks and observe that there is significant scope of protocol improvements across layers. Our model can also be used to estimate the protocol efficiency during a contact opportunity by comparing the amount of data transferred according to our model to the maximum amount of data that can be transferred with a hypothetical ideal transport behavior.

III. SHORT CONTACT MODEL

A. Simple reference model

The average available capacity, C , multiplied by the contact time, T , provides an upper bound of the amount of data that can be transferred, O . This simple model, $\hat{O}_S = CT$, is used as a baseline for comparison against the more evolved model.

B. Proposed model

For the zero packet loss case, a model to compute the expected data transfer $\hat{O}$ can be formulated as:

$$\hat{O} = C \left(T - 2.5R_S - P \left(R_S + \frac{S}{C} \right) + (2^P - 1) \frac{IS}{C} \right)$$

where

$$P = \left\lceil \log_2 \left(\frac{R_S + S/C}{IS/C} \right) \right\rceil$$

T	Contact time	(s)	C	Avg. available capacity	(bits/s)
R_S	RTT	(s)	S	Segment size	(bits)
O	Transferred data	(bits)	I	Initial window	(segments)
P	Rounds w. idling	-			

The round trip time (RTT) value R_S used in the model is the base network delay measured when the user has no concurrent connection, i.e., when any per-user buffers are empty. The parameter I represents the TCP initial window, and S represents the segment size which here is set to 11680 bits (=1460 bytes). The variable P represents the number of transmission rounds with idle time, i.e., when the received rate is constrained by the congestion window of the sender and not the available transmission resources. The model provides the expected amount of data possible to transfer during a contact period. The model makes the following assumptions:

- 1) The receiver does not employ delayed acknowledgments, but acks every received packet.
- 2) The receiver of the data does not require the reception of the final acknowledgment but can close/reset the socket by other means.
- 3) The contact period is long enough to allow the flow to ramp up to the available capacity.

Assumption 3 can be removed by adding some terms to the formulation of P . It is possible to express P as

$$P = \min \left(\max \left(\left\lceil \log_2 \left(\frac{R_S + S/C}{IS/C} \right) \right\rceil, 0 \right), \left\lceil \log_2 \left(1 + \frac{O}{IS} \right) \right\rceil - 1 \right)$$

However, such formulation is complicated by the fact that the expression for P now contains $\hat{O}$. One approach to address this issue would be by employing fixed-point iteration. With fixed point-iteration an initial value is first assigned:

$$\hat{O}_0 = C \left(T - 2.5R_S \right) - P \left(R_S + \frac{S}{C} \right) + (2^P - 1) \frac{IS}{C}$$

$$P_0 = 0$$

and then the iteration is performed

$$\hat{O}_{n+1} = C \left(T - 2.5R_S - P_{n+1} \left(R_S + \frac{S}{C} \right) + (2^{P_{n+1}} - 1) \frac{IS}{C} \right)$$

$$P_{n+1} = \min \left(\max \left(\left\lceil \log_2 \left(\frac{R_S + S/C}{IS/C} \right) \right\rceil, 0 \right), \left\lceil \log_2 \left(1 + \frac{\hat{O}_n}{IS} \right) \right\rceil - 1 \right)$$

In essence fixed point iteration assigns an initial value and then apply the function repeatedly until a sufficiently small difference occurs between successive iterations. However, not all functions will converge when using fixed-point iteration. For a function to converge to a fixed point they should be Lipschitz continuous. However, due to step function behavior that occurs for the early transmission rounds the function is unfortunately not Lipschitz continuous, as it is not injective. An additional aspect to consider is that the function maps between different topological spaces, as T can take any positive real number (i.e., continuous), while O is a natural number (i.e., discrete). Consequently, the evaluation presented here was done with the bisection method with a 0.1% tolerance.

Using the model it is possible to graph the amount of transferred data as a function of contact time. This is shown

Figure 1: Transferred data ($C=10\text{Mbps}$, $\text{RTT}=100\text{ms}$)

in Figure 1, in this example with an available capacity of 10 Mbps and a RTT of 100ms. The figure shows that the proposed model correctly captures the need for transport layer connection establishment which lead to zero data transfer for very short contact times. For the new model, the step behavior can also be discerned for low contact times around 0.5s. For longer contact times the difference between the base model and proposed model is constant in terms of bytes. Consequently the relative similarity between the models increases with increasing contact times. The relative similarity is shown in Figure 2. The figure shows the value returned from the proposed model as a fraction of the value returned by the base model. At very small contact times, the proposed model will return zero bytes of data transfer, as can be seen in the inset. The relative similarity between the models converges to one for infinitely long contact times. It can be observed that these results are only for one particular configuration of capacity and delay. Additional characterization of the model behavior for varying available capacities and RTTs are provided in Section V.

Figure 2: Relative similarity to base model

C. Model Parameters

The model utilizes several input parameters to estimate the throughput that can be achieved for a given short contact

opportunity. This section elaborates on some of these input parameters. When the model is used in a particular environment, the input parameters must clearly be tailored to the specific conditions.

1) *TCP Initial Window Size*: The initial window parameter can affect the results of the model considerably. The size of the initial window was previously standardized to three segments [1]. More recently, the recommendation of the initial window size has been changed to now experimentally allow a size of up to 10 segments [3]. The actual size of the initial window for a flow is dependent on which particular OS the sending computer is using, and the parameterization of that OS.

2) *Contact opportunity length*: The length of the contact opportunity depends heavily on the particular context of usage. As a main feature of the proposed model is to capture the transport layer behavior during the early part of the connection, the focus is on contact opportunities that are relatively short.

3) *RTT*: The observed RTT is also a factor as longer RTTs imply that the time period affected by transport layer start-up will be longer. As a measure of RTT, the time for the SYN and SYN-ACK round-trip occurring during TCP connection establishment can be used. As this RTT is measured during the three way handshake part of the connection it is commonly referred to as 3WHS RTT. The round trip time can be subdivided into several components, i.e., infrastructure-mandated and server placement components. The infrastructure-mandated component comes from the characteristics of the access link technologies used, and may result from resource allocation mechanisms such as time slotting in cellular networks. The server placement component captures the non-access part of the RTT, and if communication is performed to a server on another continent, this component will be considerable.

4) *Available capacity*: The available capacity during a short contact opportunity may vary during the lifetime of the contact. In both the reference and proposed model the expected average available capacity during the connection lifetime is used as input parameter. Depending on the particular context the model is applied to, the variation in effective available capacity during a contact time may be larger or smaller.

IV. MODEL VALIDATION

This section considers the validation of the proposed model based on measurements collected in Swedish cellular networks. The validation considers short contact periods, and also examines the magnitude of possible model correction parameters.

A. Data collection and processing

To perform the validation, empirical measurements were collected. While the model is general, a validation is concerned with a specific usage context. In this paper the validation is performed with data from an active measurement campaign using the networks of the four major cellular operators in Sweden. Measurement collection rounds were executed at two hour intervals around-the-clock and data was collected over several months. Each measurement round contains several

Figure 3: Observed data transfers versus model predictions

different run types, where each run type collects different types of data. A subset of all collected data was used for the analysis in this paper. An overview of the run types used in the evaluation are shown in Table I which also shows the number of measurement runs analyzed for each run type and operator.

Identifier	Description of run type	Nr of rounds
'long'	TCP throughput measurements for 20 MiB transfer	3.5G: 582,549,567,452 4G: 562,469,459,565
'short_random'	Completion times for flows with random sizes 1.4-320 KiB	3.5G: 418,418,417,419 4G: 416,419,418,404

Table I: Run types used in evaluation

Two measurement computers were used to perform the experiments: one server located in our lab which, via the university internal network, is connected to the Swedish University backbone (SUNET) using a 10Gbps access connection. There is also one client with four Huawei E392 USB modems, each modem with a sim-card for a specific operator. The modems can be configured to connect using 3.5G or 4G cellular network technologies. Using identical hardware avoids the problem of large variations occurring due to the particular cellular communications hardware used in experiments as reported in previous work [4]. Packet traces were collected using tcpdump and processed with tcptrace to extract transport layer metrics. TCP segment offloading (TSO), TCP metric caching and other related functionality was turned off or flushed to ensure that the various optimizations that are performed in the OS networking code and in device drivers do not interfere with the measurements. Other TCP related variables were left at their default values. The initial window size was 10 segments, and SACK was enabled. Netperf was used to generate the traffic for the short and long flows. The server and client were also directly connected to a local subnet for management purposes so that control traffic would not disturb measurements.

When performing a large number of cellular network measurements in live networks a considerable variation can be expected for several of the metrics. In addition, there might be TCP connection aborts, or losses of transport layer signaling packets may lead to very high flow completion times. In this

work we are considering modeling and parameter estimation, which can potentially be negatively impacted by highly atypical data values. We therefore employ a strategy that combines heuristics-based data exclusion and data-dependent outlier removal to create appropriate conditions for the estimation procedures.

For all run types, flows which have had a SYN or SYN-ACK retransmission are excluded from further analysis as these flows would have very high flow completion times due to the high default SYN timeout of three seconds. Similarly, flows which had retransmissions of the FIN or FIN-ACK are also removed from analysis. Flows which are incomplete, such as when a flow is closed by a RESET, are also excluded.

B. Short contact times

For short contact periods we consider contact periods consistent with what is seen in the 'short_random' experimental runs. Figure 3 shows the amount of data that is expected to be transferred using either the simple base model or the proposed model, respectively. Also shown in the graph is the actual measured values. It is clear from the figure that the base model fails to model the actual behavior, and using such base model in these particular conditions would be clearly inappropriate. The slope of the model lines corresponds to the throughput for the particular network and operator combinations. As expected the slope in subfigure 3c, for the 4G network, is the steepest. The 4G network also has the least amount of spread in the measured results. It should be noted that the measurements here are used for model validation. The relative performance between 3.5G and 4G networks as shown here, and between the different operators, should not be generalized as the results shown here represent only the particular conditions where the measurements were collected.

C. Model fitting

The proposed model allows us to estimate the expected amount of data that can be transferred during a short contact period given a set of input parameters. The model makes a number of assumptions:

Figure 4: Model error before(left) and after(right) model fitting, proposed model

Figure 5: Model error for simple model, 4G Operator 3

- 1) The input parameters such as RTT are equal to their actual values, and does not vary over the lifetime of the contact period.
- 2) The server is never application limited.
- 3) No non-probing packet losses occur. Wireless access techniques typically employ link layer mechanisms to shield the transport layer from losses.

If the assumptions hold, the model is expected to provide a good representation of the behavior. In reality, these assumptions however do not always hold as there for example will be variations in the parameters assumed to be static. The difference between the value predicted by the model, and the actual observed value can be the result of random variations that are caused by random processes in the environment. Alternatively, the difference can result from a systematic error either in the model or the modeling assumptions. To examine to what extent there could be a systematic error present, we performed a Levenberg-Marquardt [13] regression using an auxiliary variable. If there is a systematic error, then this regression should lead to coefficient values differing from 1 when fitted against the observed data.

In the current validation Time-of-Day variations are not compensated for, even though it is possible to derive ToD effects from the data set [7]. In the general case, however, it is not necessarily the case that a data set is available for ToD effect compensation. In this validations, the included ToD variation will increase the variance, but not contribute any bias. To perform the model fitting, the proposed model is re-formulated as an expression for determining a flow completion time L_s instead of a data amount O . This avoids the trouble of requiring iterative methods to solve the expression as discussed earlier. The data set used for fitting provide both L and O , so it is indifferent which is the sought for variable used in the expression employed for model fitting. For the model fitting case we can also have

further parameterization of the model. We introduce one variation of the model where a scale factor F_C is multiplied to the available capacity (i.e., long flow throughput), and the resulting model now becomes:

$$\hat{L}_S = 2.5R_S + \frac{O}{F_C C} + P \left(R_S + \frac{S}{F_C C} \right) - (2^P - 1) \frac{IS}{F_C C}$$

With this new model it is possible to perform nonlinear least squares regression to find the value of the F_C scale factor which results in the smallest prediction error. To perform the least squares regression we employ the Levenberg-Marquardt approach. In these evaluations the median of the long term throughput per operator and network is used as the value for C in the model.

The results from the model fitting is illustrated in Figure 4. The left graph of each subfigure (red) shows the error terms for a given measurement (network technology and operator) before any model fitting. The right graph of each subfigure (green) shows the error terms after the model fitting has been performed. It can be seen in the figures that the model fitting changes the distribution of the errors so that they become more symmetrically distributed around zero. In many cases a short contact model will be used to estimate the amount of data that can be transmitted during a contact opportunity, and it is preferable that the model errs on the side of caution. Typically, more utility would be provided by a model that allows the planned transfer of the predicted size to complete in full, rather than a model that strive for higher utilization but often cannot complete the planned transfers due to overestimation. Model fitting allows the characteristics of the model to become more symmetric, which would be useful for percentile-based statistical trade-offs between planned transfer completion probability, and transmission resource utilization. For comparison, the results from a similar fitting done for the simple model is shown in Figure 5. The unfitted model error is above that in Figure 4c, and it is also clear that the fitting fails to compensate for the shortcomings of the model.

V. SAMPLE RESULTS

The model can be used to explore where in the parameter space the transport layer behavior is of such relative importance that a simplified base model would lead to significant modeling errors. Figure 6 shows the relative similarity between the proposed model and the simple base model. Three different contact times are shown. For the shortest contact times, 1s

Figure 6: Relative similarity between models at various contact times (IW=10)

and 3s, the results show that the simple model would be inappropriate for practically any combination of RTT and available capacity. Also for the 10s contact time the model difference may be worthy of deliberation.

The similarity between models can also be viewed as a proxy for protocol efficiency. A low similarity value in Figure 6 implies that the protocol efficiency will be low and that the available transmission resources will go underutilized. In energy-constrained mobile settings such underutilization will put unnecessary additional strain on the energy resources. Operating conditions in the blue to red fields should thus be avoided. The results can also be used to judge the benefit of decreasing the server placement component of the RTT. Moving server functionality closer, in a RTT sense, will improve the efficiency. The magnitude of this improvement can be seen visually in the figure, as well as calculated.

VI. CONCLUSIONS

This work has presented a model of data transfer for short contact times. The model takes the transport layer characteristics into account, which for short contact times can have a significant effect. The model also highlights the need to strive for close placement of the communicating entities, as higher than necessary RTTs also negatively impacts the performance for short contact time transfers. The model has general applicability, and cellular measurements were used to compare model output to measured data, as well as examining the benefits of model fitting. The model can be used to provide insights into the operating conditions over a large range of the parameter space.

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