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CAPACITY OF THE SWEDISH COPPER ACCESS NETWORK

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ABSTRACT

This paper aspires to indicate how much broadband communication the Swedish copper access network can offer when developed to its full potential. We look at a number of different infrastructure deployment scenarios and calculate the Shannon capacity of the copper loops using different deployment-dependent loop-length distributions with different deployment-dependent and technology-dependent noise models. We investigate both deployment from the central-office and from the cabinet. We consider non-cooperative scenarios, where the deployment is carried out system by system following only the mandatory standardised rules and every line is operated autonomously without cooperation of transceivers. We also investigate scenarios with mechanisms for better exploitation of the access plant through dynamic spectral management, multiple-input multiple-output techniques, and common-mode aided interference suppression. The choice of elementary parameters, like transmit power and background noise, is based on today's digital subscriber line (DSL) standards. Statistical models are used for the main parameters of the network topology. Note that we are not calculating a capacity in an information theoretic sense, but rather a data rate under given constraints.

1. INTRODUCTION

The copper infrastructure represents a valuable resource for the deployment of broadband services and is today the dominating medium with about 60% of all broadband connections worldwide. Sweden has about 8.000.000 copper lines installed out of which roughly 6.000.000 are currently in use. In order to obtain an idea about the long-term potential of this copper as an access medium, we calculate the Shannon capacity of the Swedish copper access network. We investigate a number of different scenarios, each with different deployment and technology options, and thus associated with different infrastructure investments [1].

A number of basic parameters, like transmit power limits, power spectral density constraints or spectral bandplans are chosen based on current versions of digital subscriber line standards. Statistical models are introduced for the parameters of the network topology, like loop length distribution, wire gauge and binder sizes.

The paper is organised as follows. We first overview the math that we need for our calculations and provide references to the results we invoke. A brief description of the topology and structure of the Swedish copper access network follows. Then we describe the scenarios we investigate, comment on their requirements in terms of investments, technology, standardisation, and regulation, and present the associated capacity estimates in the form of total capacity of the network, average capacity per residential customer, and minimum capacity that 90% of the customers could get. Finally, a discussion of the results concludes the paper.

2. MODEL

The main impairment of a twisted-wire pair on the transmit signal is dispersion in time, or equivalently, frequency-selective attenuation. Due to electromagnetic coupling among wires in a multi-pair cable, excitement of the near-end port of pair No. k according to the transmit signal $x_k(t)$ causes signal components correlated with $x_k(t)$ at both the near-end ports (near-end crosstalk, or short NEXT) and the far-end ports (far-end crosstalk, or short FEXT) of all neighbouring pairs.

When all loops of a cable are properly terminated (e.g., with modems), a K-pair cable can be modelled as a vector-valued linear time-invariant (LTI) system

$$\mathbf{y}(t) = \mathbf{H}(t) * \mathbf{x}(t) + \mathbf{n}(t) \tag{1}$$

where $x_k(t)$ and $y_k(t)$, the kth elements of the vectors $\mathbf{x}(t)$ and $\mathbf{y}(t)$, denote the input signal at the near-end port and the output signal at the far-end port of pair No. k. The element in the mth row and nth column of the channel impulse response matrix $\mathbf{H}(t)$ models the coupling path from the near-end port of pair No. n to the far-end port of pair No. m and $*$ denotes linear convolution. The kth main diagonal element of $\mathbf{H}(t)$ models the insertion loss of pair No. k and the off-diagonal elements model the FEXT paths. Front-end noise and thermal noise, hereinafter summarised under the term background noise, is represented by $\mathbf{n}(t)$ and can be modelled well by an i.i.d. Gaussian

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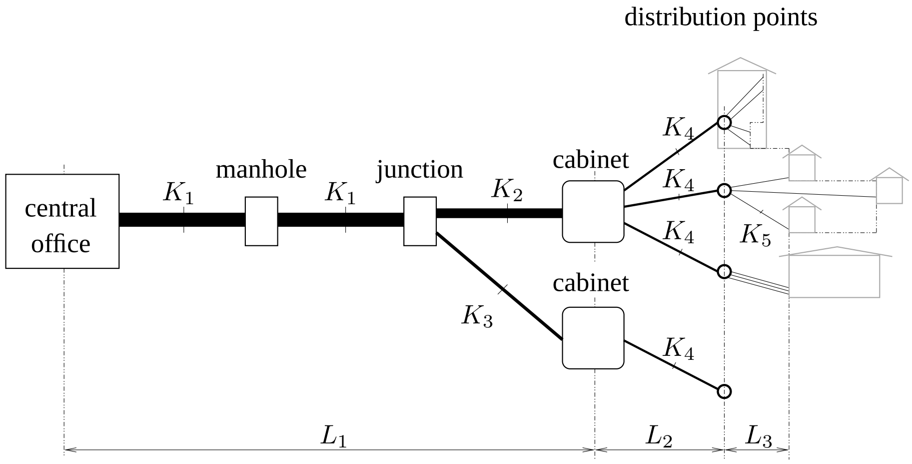

Figure 1. Generic topology of the Swedish copper access plant.

random process. Furthermore, $\mathbf{n}(t)$ includes interference originating from crosstalk, which can be modelled as correlated Gaussian process. Note that this model considers only simplex transmission, i.e., transmission from the near-end to the far-end. In a non-cooperative scenario, where the transceivers operate autonomously, the FEXT component present in the receive signal $y_k(t)$ of the kth user caused by the $K-1$ other users constitutes interference for user k. This holds for each of the K users. In a cooperative scenario, however, FEXT turns into a useful signal component. NEXT introduced by transmitters located at the same side always constitutes interference. Unless the cable is very short or there is a severe near-far problem, the NEXT power spectral density (PSD) level is considerably higher than the FEXT PSD level. Consequently, most digital subscriber line (DSL) techniques that exploit high-frequency regions avoid NEXT by frequency division duplexing (FDD). Depending on the loop length, NEXT residuals resulting from out-of-band power may have to be taken into account. Apart from better FDD filters, more advanced techniques can be employed. In case the transmitters are co-located and have mutual access to other users' transmit signals, NEXT cancellation can be employed by extending echo cancellation techniques to the case when there are more sources. In case the transmitters operate autonomously, the NEXT component can be estimated and subsequently eliminated by cancellation up to a residual [2]. Considering these techniques, it is reasonable to assume a NEXT-free environment. The capacity results presented in the following denote the totality in both directions. An arbitrary split between upstream (US) and downstream (DS) rate can be achieved by good FDD implementations or discrete multi-tone (DMT) modulation combined with synchronisation of transceiver clocks, which allows arbitrary interleaving of US and DS bands, in an implementation proposal known as "zipper" [3].

The wireline channel is usually assumed time-invariant with stationary noise processes. Neither of these two assumptions is completely true. The response does change due to variations of environmental conditions (most often very slowly, though, due to effects like ice forming or thawing around a wire) and the parameters of the noise process change drastically if a user in the bundle goes online or offline. Furthermore, impulse noise, which is mainly a problem occurring at the customer side (due to mixers, electrical heaters, faulty power supplies, etc.) and ingress from radio services, referred to as radio frequency interference (RFI), are of non-stationary nature. In the following, we assume that appropriate counter-measures are taken to mitigate the impact of non-stationary noise and interference. Impulse noise can be taken care of on coding level and several techniques to combat RFI, both before and after the receiver's analogue-to-digital converter, have been investigated [4][5].

Although, a single loop can be modelled as an LTI system with deterministic parameters, a statistical view has to be taken when looking at many pairs, since the parameters vary from pair to pair. Hereinafter, we apply 1% worst case models, which means that on average 99% of the customers are better off than this. Models for insertion-loss functions and crosstalk coupling functions, which mainly depend on loop length and wire gauge, have been found and verified by measurement campaigns [6][7]. For a given frequency, there is a considerable variation in the magnitude of the crosstalk coupling functions seen between an arbitrary pair and the $K-1$ others. For any given frequency, the crosstalk originates mainly from a few pairs, which have the strongest coupling to the victim pair. This holds for any frequency, however, the dominant source pairs vary. Consequently, it is a good idea to find an equivalent coupling function representing the resulting crosstalk originating from several pairs excited with equal power spectral densities by means of averaging over the coupling functions. A frequently used model for this coupling function, referred to as crosstalk power sum, has been confirmed by measurements [8]. In the following, we will use a slightly modified version, which yields the power sum coupling function

$$H_{\text{fext}}(L_{\text{c}}, K, f, H_{\text{loop}}(f)) = \frac{L_{\text{c}}}{L_0} k_{\text{fext}}(K) f^2 |H_{\text{loop}}(f)|^2,$$
$$L_0 = 0.3048\,\text{m}, \quad k_{\text{fext}} = (K/49)^{0.6}\, 9 \cdot 10^{-20}, \tag{2}$$

where L_c is the coupling length in m, K denotes the number of pairs in the bundle, f denotes the frequency in Hz, and $H_{\text{loop}}(f)$ is the average insertion loss of the pairs in cable. Note that the coupling length L_c may be shorter than the cable length, which determines $H_{\text{loop}}(f)$. The model (2) aspires to treat the case when a pair splits off from the bundle before the end.

3. SWEDISH COPPER ACCESS PLANT: TOPOLOGY AND PARAMETERS

The generic topology of the Swedish copper access network is depicted in Fig. 1. In principle it is a star network, or a set of star networks, in practice it consists mostly of star networks with a little bit of a mess added. The "messy" part lies in that sometimes cables from different branches of a "star" cross or join each other, so it is not perfectly regular. The centre of each star is a central office (CO) from which thick bundles of twisted copper pairs protrude in many directions. A central office may have anything from 100 pairs to, say, 50.000 pairs going out. The bundles vary in size from 100 wire pairs to thousands, depending on the location and age of the central office. The wires are often referred to as either "paper" or "plastic", which denotes the type of insulation. Older cables are often paper-insulated, newer cables have plastic insulation. Bundles with paper cables need to be protected against humidity and are often surrounded by pressurised air. Old, pressurised, paper-insulated cables require far more maintenance than modern "plastic" bundles. Quite often the cables leading out from a central office are paper insulated while the final section leading to the customer is plastic, simply because it is newer. As cities grow, new areas are added with new copper wires, sometimes in the form of extensions of older, unused pairs, that were available in some nearby cabinet.

The average length of a loop in Sweden ($L_1+L_2+L_3$ in Fig. 1) is about 1.5 km; the average length of the bundle, or the part of a bundle between the central office and the cabinet (L_1) is about 1.2 km, and the average length of the loop between the cabinet and the customer (L_2+L_3) is about 300 m. The distribution of the loop length between the central office and the customer that we use in this paper is depicted in the upper plot of Fig. 2. There are few loops shorter than 300 m or longer than 6 km. When modelling crosstalk characteristics in bundles from the central office, it is reasonable to consider a bundle strength (No. of pairs per bundle) of only $K = 100$, although this is the smallest available. Bundles with fewer pairs occur very rarely and bundles with more pairs hardly match the crosstalk models since the distances between pairs grow with the No. of pairs, which makes bigger bundles look smaller from an average crosstalk power point-of-view.

K_4	10	30	50	100
$\text{Prob}\{K_4\}$	0.05	0.05	0.3	0.6

Table 1. Distribution of bundle size K_4 going out from the cabinet.

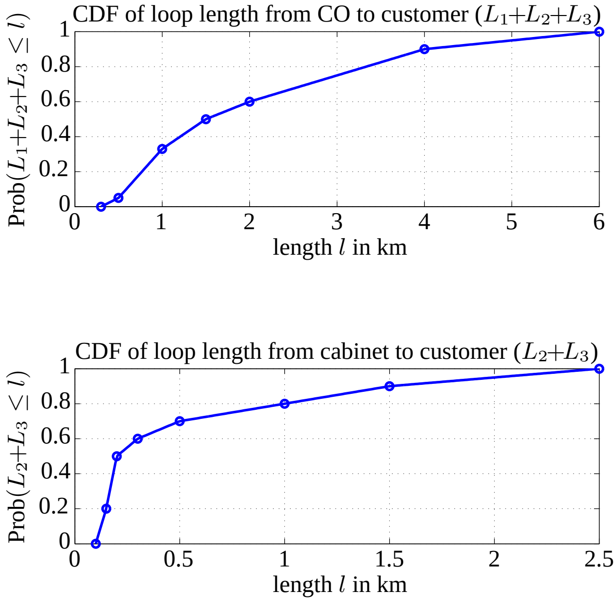

Figure 2. Cumulative distribution function of loop length from central office to customer (upper plot) and from cabinet to customer (lower plot).

Our assumed distribution of bundle strength from the cabinet, i.e., the No. of pairs per bundle, going out from the cabinets, is given in Table 1. The number of customers served from the cabinet is normally a few hundred. Since we are interested in the capacity, we assume full saturation of all cables. The most common bundle size at the cabinet is 100. The lower plot of Fig. 2 depicts the distribution of the loop length between the cabinet and the customer. The loop length ranges from 100 m till 2.5 km.

A good model of the electrical properties of average loop installed in Sweden is the ETSI 0.5 loop. This is a European (ETSI) model for a plastic-insulated twisted pair with a 0.5 mm diameter of the copper core.

4. CAPACITY RESULTS

From the above discussion, it follows that the Gaussian model (1) is reasonable to find an estimate of the capacity. Although, certain assumptions about cooperation of users in principle turn the problem into a broadcast channel or a multiple-access channel, computation of the total capacity is much simpler. In fact, it suffices in all cases to determine the per-loop capacity [9] given by

$$C = \int_{f \in B} \log_2 \left(1 + \frac{S(f)}{N(f)\Gamma}\right) \mathrm{d}f, \qquad (3)$$

where $S(f)$ and $N(f)$ are the signal PSD and the noise/interference PSD measured at the receiver input, respectively, and B specifies the available frequency region. The noise margin Γ takes into account that we cannot apply coding schemes that imply arbitrarily high complexity, latency or memory. Furthermore, the noise margin also accounts for imperfections in the implementation of measures to combat non-stationary noise and interference discussed above. It should be mentioned that we are not calculating a capacity in an information theoretic sense. Since we assume a mask for the PSD of the transmit signal and the transmit power is high enough so that we can exploit the mask, the spectral shape of the transmit signal and thus its correlation are pre-determined. In other words, there is no need for waterfilling. Consequently, we are rather calculating a data rate under given constraints instead of a capacity. In the following, we use the term “capacity” for results of (3) obtained with $\Gamma = 0$ dB and “predicted rate” for results obtained with a margin $\Gamma = 6$ dB.

Two principally different scenarios are considered. First, a non-cooperative environment is investigated. The deployment is carried out on a line by line basis following only the mandatory standardisation rules. Every line is operated autonomously, no cooperation between transceivers is assumed. Consequently, every line acts like a disturber for neighbouring lines due to crosstalk.

Secondly, a cooperative environment is considered. This case includes mechanisms for exploiting the access plant in the best possible way from engineering perspective. Here, since the transceivers serving a bundle are co-located and owned by the same company, they can cooperate. This is the case for deployment both from the central office and from the cabinet. In DS direction, all transmitters serving a bundle can cooperate and the resulting scenario is modelled by a broadcast channel. Since we are only interested in the sum capacity, it is sufficient to assume that FEXT is eliminated by pre-coding. This yields an upper bound for the achievable rate. An implementation suggested for this case is vectored DMT [10]. In US direction, cooperation of all the receivers serving a bundle, which is again feasible since they are co-located, yields a scenario which is best modelled by a multiple access channel. Also in this case, an upper bound for the sum rate can be found by assuming that FEXT is eliminated by means of cancellation [10].

Additionally, different modes in a multi-conductor system can be exploited. As an example, the common-mode signal at the receive side, which corresponds to the arithmetic mean of the voltages measured between each conductor and earth, can be used in the receiver. Exploiting the common-mode signal, which we call common-mode aided communication, can yield a significant increase in rate for certain scenarios [11-14]. In this paper, we do not consider the direct impact of these schemes on the rate results but we rather view these methods as supporting techniques to achieve the predicted rates.

In the following, the scenarios and the corresponding assumptions are presented. Tables 2 and 3 summarise the minimum capacity values and the minimum predicted rate values that 50%, 90%, and 99% of the loops achieve. The predicted rates per loop versus loop length for deployment from central office and deployment from cabinet are shown in Fig. 3 and Fig. 4, respectively.

p	50%	90%	99%
CO	37.9	7.4	3.8
CO cooperative	61.1	8.5	4.1
cabinet	173.9	38.3	18.2
cabinet cooperative	643.4	60.4	23.5

Table 2. Minimum predicted rate ($\Gamma = 6$ dB) per loop in Mbps of p percent of the loops for each of the four scenarios.

p	50%	90%	99%
CO	52.3	9.5	4.8
CO cooperative	75.8	10.6	5.0
cabinet	232.3	52.4	23.9
cabinet cooperative	703.2	75.0	29.1

Table 3. Minimum capacity ($\Gamma = 0$ dB) per loop in Mbps of p percent of the loops for each of the four scenarios.

4.1. Deployment from central office

In this scenario all users are served from the central office, which is the case in Sweden today, and in almost all European countries. (To the authors' knowledge, only Belgium has commercial cabinet-deployment in Europe at the time of writing.)

4.1.1 Non-cooperative scenario

A straightforwardly continued deployment of DSL systems following today's deployment paradigm (only CO deployment) and with today's regulatory framework (physical unbundling), would lead to this scenario. We assume a flat -40 dBm/Hz transmit PSD, noise margin $\Gamma = 6$ dB, no POTS, consequently a frequency range from 0 Hz to 30 MHz, FEXT coupling-length $L_\mathrm{c} = L_\mathrm{loop} - 99$ m, exclusively 100-pair bundles as discussed above, loop length distribution according to Fig. 2, NEXT-only environment, and a background noise PSD level of -125 dBm/Hz. The total sum rate for all the 8 million loops amounts to

$$C_\mathrm{co} = 3.8 \cdot 10^{14}\ \text{bit/s},$$

which yields on average roughly 48 Mbps per loop or 43 Mbps per Swede. In principle, we apply (3) to each loop, where $N(f)$ depends, apart form the background noise level, on length, FEXT coupling length, and bundle size of the corresponding loop.

4.1.2 Cooperative scenario

A continued deployment according to today's situation in the U.S.A. would correspond to this scenario, if the appropriate technological refinement were added. Assuming cooperation of the transceivers that serve a bundle from the central office, the rate under the above assumptions is given by

$$C'_\mathrm{co} = 9.9 \cdot 10^{14}\ \text{bit/s},$$

which yields on average roughly 123 Mbps per loop or 110 Mbps per Swede. Fig. 3 depicts the predicted rate per loop versus loop length for both the cooperative and the non-cooperative scenario. The rate for the cooperative scenario is more than three times higher than the rate for

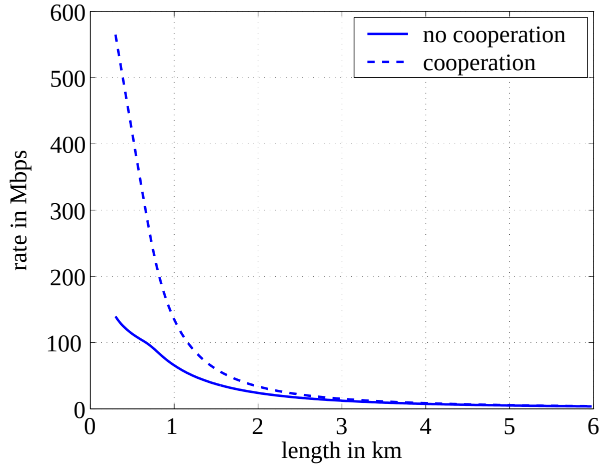

Figure 3. Predicted rate versus loop length for central office deployment.

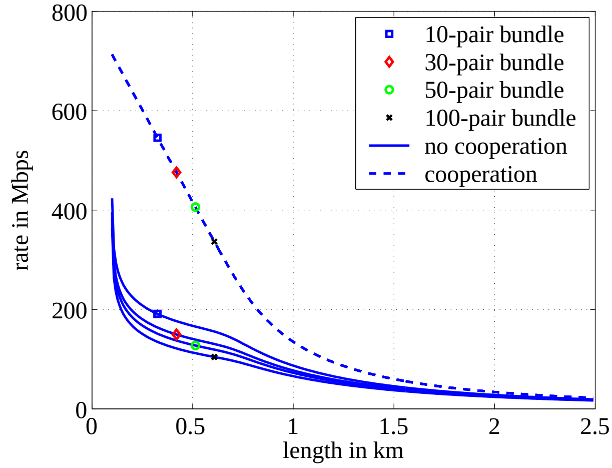

Figure 4. Predicted rate versus loop length for cabinet deployment.

the non-cooperative scenario for very short loops, however, there are only very few of them. For the average length of 1.5 km, this gain only amounts to a factor of 1.5. Essentially, in the cooperative scenario the FEXT is eliminated. The longer the loops, the lower is the FEXT level. Consequently, the performance gain on long loops is limited by signal attenuation and background noise.

4.2. Deployment from cabinet

In this scenario, the majority of users is served from cabinets. The remaining users, which are served directly from the central office, are few and very close to the central office. Consequently, we assume their distance distribution to be the same as for cabinet-deployed customers.

4.2.1 Non-cooperative scenario

With flat -40 dBm/Hz transmit PSD, noise margin $\Gamma = 6$ dB, no POTS, FEXT coupling-length $L_c = L_{loop} - 99$ m, bundle-size distribution according to Table 1, bundle length distribution according to Fig. 2, NEXT-only, frequency range 0 Hz to 30 MHz, and a background noise PSD level of -125 dBm/Hz, we obtain a total sum rate for all the 8 million loops of

$$C_{cab} = 1.2 \cdot 10^{15} \text{ bit/s},$$

which yields on average roughly 154 Mbps per loop or 136 Mbps per Swede.

4.2.2 Cooperative scenario

Assuming cooperation of the transceivers that serve a bundle in the cabinet for all the bundles, the total sum rate under the same assumptions as for the non-cooperative scenario is given by

$$C'_{cab} = 3.9 \cdot 10^{15} \text{ bit/s},$$

which yields on average roughly 486 Mbps per loop or 432 Mbps per Swede. The predicted rate per loop versus loop length is shown in Fig. 4. The rate for the cooperative scenario does not depend on the bundle size, since FEXT, whose PSD level is bundle-size dependent, is eliminated. For the average loop length of 300 m, the rate for the cooperative scenario is roughly 2.5 times the rate for the non-cooperative scenario. Note that the dramatic rate increase for very short loops in the non-cooperative scenario is a consequence of assuming a FEXT coupling length that is 99 m shorter than the loop length. For a loop length close to 100 m, the FEXT coupling length is close to 1 m, i.e., there is essentially no FEXT. Consequently, the rate tends towards the rate achieved in the cooperative case.

5. DISCUSSION

It is in the nature of the copper network to provide a lot of capacity for the customers that are close to the central office or the cabinet (i.e., for those that have short loops), and little for the ones further away. This is illustrated by the rapidly decreasing curves in Fig. 3 and Fig. 4. Our results indicate that MIMO-techniques, invoked in the ”cooperative” scenarios, yield a multiple of the predicted rate obtained in the non-cooperative scenario for a few customers (cf. 50% numbers), but result in small improvements for the customers that have a low rate already in the non-cooperative scenario (cf. 90% numbers). This is unfortunate since the economical advantage of bringing new, yet to be conceived, ultra-high bandwidth services to a few, is much smaller than increasing the market for already existing, or foreseeable, services.

Since the beginning of Internet, there has been the discussion of how much bandwidth can/will a household consume. If we would like to guess for how long copper can be the dominating broadband provider, we need to take a look at this aspect, too. As an example of bandwidth, one single Mbps is sufficient to download one DVD-movie on a double-sided DVD per day, or two movies on single-sided DVDs, with extra margin for surfing, e-mailing, and other low-bandwidth services. Five Mbps would be five to ten DVD-movies per day. (This is not a part of the downloading debate, it is simply an illustration of how much bandwidth one Mbps is.) However, today IP-TV, television over DSL, is available. Viewing a DVD quality movie in real-time would require about ten Mbps (no extra-material, a single soundtrack), and a TV-channel perhaps half of that. Watching an IP-TV-channel and web-surfing would be possible for most with today's CO-based deployment paradigm, cf., the CO-90% rate in Table 2. However, streaming a DVD-movie, watching an additional TV-channel, and running some other services simultaneously, a migration from the central office to the cabinet will be necessary for many customers. This corresponds to moving from the CO-90% rate to the cabinet-90% rate, which should last a while, especially as the rate for most customers is given by the cabinet-50% rate.

As a final note, we would like to point out that although we have invested a lot of work and math into our calculations, our numbers are not better than guesses. They might be fairly accurate (and we hope so), but by spending a lot of time in the field, one learns that predicting capacity or rate is probably even more difficult than predicting, say, weather.

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