INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Trec

Network Theory and Communications

Rocquencourt

THEME 1B

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1. Team

TREC is a joint INRIA-ENS project-team.

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2. Overall Objectives

TREC is a joint INRIA-ENS project-team. It is focused on the modeling and the control of communication networks. Its methodological activities are combined with projects defined by industrial partners, notably by Alcatel and France Télécom. The following four principal axes are being developed:

- packet network communication control: admission control, flow regulation, congestion control, traffic analysis in controlled networks,
- modeling of cellular and ad hoc wireless networks: coverage and load analysis, power control, evaluation and optimization of the transport capacity,

- study of the stochastic network dynamics, in particular by means of algebraic methods,
- developing tools of stochastic geometry and spatial point processes: Voronoi tessellations, coverage processes, spectral analysis.

3. Scientific Foundations

Here are the main scientific subjects studied in each of the four principal axes.

- Modeling and control of communication networks. By control, we mean here the notions of admission control, flow regulation and feedback control à la TCP, the understanding and improvements of which are major challenges within the context of large networks. Our aim is a mathematical representation of the dynamics of the most commonly used control protocols, from which one could predict and optimize the resulting end user bandwidth sharing and QoS. The design of scalable simulators that could be used for the dimensioning of large IP networks is a first practical outcome of this line of research. The design of multicast overlays based on these common transport protocols is another line of research that is directly linked to the understanding of the dynamics of these protocols.
- Modeling and optimization of cellular and ad hoc wireless networks. The main focus of this line of thoughts is on the analysis of CDMA networks and of MANETs. A new mathematical representation of interferences based on shot noise has led to a variety of results on coverage and capacity of large CDMA networks when taking into account intercell interferences and power control. The mathematical analysis of the interference and power control problems allowed for the definition of new decentralized admission and congestion control protocols. Our goal is here to estimate and/or maximize the load of UMTS networks. Connectivity and MAC layer protocols for MANETs are currently investigated using a similar approach (additive and max shot noise processes). A new spatial Aloha MAC protocol was proposed that optimizes the transport capacity for ad hoc networks with relaying. The goal is to determine MAC parameters that auto-adapt to the spatial population of users.
- Theory of network dynamics. TREC is primarily interested in pursuing the elaboration of a stochastic network calculus, that would allow the analysis of network dynamics by algebraic methods. The mathematical tools are those of discrete event dynamical systems: semi-rings (max, plus) and inf-convolutions, as well as their non linear extensions (topical and non expansive maps, monotone separable framework); the main probabilistic tools within this framework are ergodic theory, asymptotic analysis, Lyapounov exponent analysis, perturbation analysis and large deviations. The link with certain methods of particle systems such as hydrodynamic limits and mean field limits has allowed us to assess properties of networks of infinite dimension or infinite population, with quite promising implications to the scalability of TCP based overlay networks.
- Stochastic geometry and the theory of point processes. The theory of point processes on the real line plays a key role in teletraffic analysis. The main mathematical tools studied within this framework are Palm calculus, stochastic intensity and Gibbs fields. Stochastic geometry is particularly useful in all subdomains of communications where planar or spatial components are present: access networks, local loop, multicast trees, distributed games, hierarchical network architectures, in addition to all the wireless network problems listed above. TREC's favorite tools within this framework are Voronoi tessellations, coverage processes and percolation. See http://www.di.ens.fr/~trec/sg/.

4. Application Domains

We interact with the following industrial partners: France Télécom, Alcatel and IBM.

- The collaboration with FT is focused on two types of applications: the economic analysis of the network which is important because of strong competition between operators and the analysis of protocols having spatial components. Notably, works are focused on the coverage and capacity of the CDMA/UMTS networks. The current work bears primarily on macrodiversity in UMTS, multisectorial antennas in CDMA, distributed power and admission control for UMTS. Three patents were filled on these questions, one by INRIA and two jointly by INRIA and FT.
- The work with Alcatel is focused on TCP over OBS, xDSL access architecture design, DSLAM optimization, VP shaping, scheduling in the CPE, load balancing in core networks. Two INRIA patents were filled on the generic tools underlying the interaction with Alcatel.
- With IBM, we work on the design of multicast overlays, both with and without backpressure mechanisms. IBM filled a patent on the matter with INRIA-ENS co-authors.

5. Software

5.1. N2N Software

Participants: François Baccelli, Dohy Hong, Jean-Baptist Lapeyrie, Laurent Fournié.

Key words: *simulation*, *TCP*, *access router*, *core router*, *HTTP traffic*, *quality of service*.

Based on the simulation methodology of the interaction of a large number of TCP connections sharing a few or a large number of routers, a prototype of software has been developed. The tool allows one to study the characteristics of the rates obtained by each type of users or applications under realistic assumptions on traffic (mixing HTTP, Voice, Mail, Video etc) from a detailed description of each network element.

A start-up, N2NSOFT, was created in September 2003 in order to make commercial software using this methodology. N2NSOFT is now incubated by INRIA-Transfert.

From August 2003 to January 2004, Laurent Fournie did an intern-ship in N2NSOFT. He worked on the creation of a 802.11 wireless network simulator. The goal is to integrate such networks in a larger wired architecture and to integrate it in the fluid model of N2NSOFT. To take collisions and losses on MAC level into account, he developed a hybrid model, where 802.11 interactions are handled at the packet level. This work is linked to a collaboration with Thomson Multimedia.

From July 2003 to August 2004 Jean-Baptiste Lapeyrie did an internship in N2NSOFT. His aim was to evaluate and improve new dynamic routing algorithms in core networks. This work is linked to a collaboration with Alcatel Marcoussis.

6. New Results

6.1. Analysis and optimization of flow-control protocols

Key words: *TCP/AQM*, *TCP/IP*, *Reno*, *Tahoe*, *AIMD flow model*, *feedback control*, *stability*, *delay compensation*, *optimal performance*, *congestion prevention/control*, *additive increase multiplicative*, *decrease algorithm*, *sporadicity*, *regulation*, *multicast*, *(max plus) algebra*, *dynamical system*, *simulation*, *wavelet*, *fractal*, *synchronization*, *fairness*.

Participants: François Baccelli, Augustin Chaintreau, Dohy Hong, Ki-Baek Kim, David McDonald, Julien Reynier, Thu Ha Dao Thi.

A methodology to analyse traffic and congestion control mechanisms is a prerequisite for operators to do resource planning (buffer capacities and bandwidth) capable of handling every kind of trafic mix (voice, video and data) ensuring predefined end to end QoS bounds for various functioning parameters. Several research actions were pursued on the matter.

6.1.1. Fluid modeling of TCP

The TCP/IP protocol is based on the AIMD (Additive Increase, Multiplicative Decrease) dynamic window flow control.

6.1.1.1. The billiards model

When the round trip time RTT of each flow is assumed constant (small buffer assumption), the evolution of the rate dynamic can be described by a piecewise affine dynamical system with a fundamental parameter that is the synchronization rate. This is the billiards representation of the interaction of TCP flows over arbitrary link and router topologies, which is described in [9] (paper nominated for best paper award in Infocom 03). This representation is believed to be the first model that captures the stochastic dynamics of the Tail Drop case in a global and tractable way.

6.1.1.2. Aggregated Traffic

Even under very simplifying assumptions (homogeneous traffic, constant RTT, packet losses independent of the rate), the statistical analysis based on wavelets analysis show a non-trivial behavior of the aggregated traffic of multi-fractal type (cf. [8]). These results suggest a concrete physical explanation of the multi-fractal characteristic observed in TCP flows at small time scale.

6.1.1.3. Dynamics of queue size under TCP

In [22], the fluid TCP model was revisited in order to study the interaction of TCP and of the queue size dynamic. An explicit solution of the non-linear differential equation is proposed for the dynamics of the throughput, the queue dynamics and delays. We showed that if the queue never empties, we have a very non-intuitive rate dynamic and that in particular the ratio $w(t)/rtt(t)$ is a constant. We test the analytical solution by comparison with NS2 simulation results.

6.1.1.4. The snake model

We proposed a new model of TCP interaction dynamic called the snake model [28]. We showed that this model explains in particular fine interaction features of the interaction of several TCP flows (which in some cases may be quite strange). The model can also allow one to study the final state characteristics of TCP's dynamic.

6.1.2. Mean field analysis

Mean field limits have allowed us to assess properties of networks of with very large population.

6.1.2.1. Interacting HTTP flows

This work describes the transition of multiple HTTP connections from a lossless, congestion free steady state to a state of congestion with reduced transmission rate. It is the subject of the publication [33] that has been submitted to ACM Sigmetrics.

6.1.2.2. Modeling RED

In parallel to the AIMD model, we used the mean field method to describe TCP with differential equations. This approach allowed us to analyse RED ([37] and is now being extended to the case of non persistent sources through one router.

6.1.2.3. Mean field convergence of a model of multiple TCP connections through a buffer implementing RED

This work provides a new approach to mean field convergence. If N stochastic dynamical systems are coupled together through the use of a common resource one may describe the entire system via a histogram of all N states. In the mean field limit as $N \to \infty$ this histogram tends to a deterministic density. This situation occurs for instance when describing the windows of N TCP/IP connections multiplexed through a common buffer. This work is the subject of the publication [27] that has now been accepted subject to revision by the Annals of Applied Probability.

6.1.2.4. TCP throughput analysis under transmission error and congestion losses

In [20], we analyzed the performance of a large population of long lived TCP flows experiencing random packet losses due to both random transmission errors and congestion created by the sharing of a common tail drop bottleneck router. We proposed a natural and simple model for the joint throughput evolution of the set

of TCP sessions under such a mix of losses. For the case of Poisson transmission errors, we showed that the asymptotic model where the population tends to infinity leads to a well defined and tractable dynamical system. In particular, we derived the mean value of the throughput of each session as a function of the transmission error rate and the synchronization rate in the bottleneck router. The large population asymptotic model has two interesting and non-intuitive properties:

1. there exists a positive threshold (given in closed form) on the transmission error rate above which there are no congestion losses at all in steady state;
2. below this threshold, the mean throughput of each flow is an increasing function of the transmission error rate, so that the maximum mean value is in fact achieved when the transmission error rate is equal to this threshold.

The finite population model and models based on other classes of point processes was also studied. In particular, a sufficient condition was obtained for the existence of congestion times in the case of arbitrary transmission error point processes. These research results will be presented at Infocom 04 in Hong Kong.

6.1.3. Modeling OBS using the AIMD model

Future operators of core networks will use Optical Burst Switching (OBS). OBS is a new technology which enables core routers to route directly light without any electrical transcription. This increases capacity. Therefore it is necessary to evaluate TCP congestion inside the optical core network. Today's technology makes it necessary to group packets into larger transmission units, the bursts. Thanks to the AIMD model, we have studied how TCP congestion harms the core OBS network when congestion occurs inside the network. These results have been published at ITC jointly with Alcatel Bell's Network Strategy Group ([10]).

6.1.4. Multicast overlays

In contrast to an IP-protocol-supported multicast group, the packets of a multicast group that is supported by an overlay tree are not duplicated inside of the IP network, but by a certain number of users. The information is sent from the root to a first set of users having distinct TCP connections. Each user receiving packets and not being at the extremity of a branch of the multicast tree, should retransmit the packets to a further set of users, for which he plays the role of a source, using different TCP connections.

For this mechanism to work, each user has to keep in its memory the transmitted information, even if he does not use it any more, until it is acknowledged by the users attached to him. In a first step, we supposed that each user has enough memory to support the relaying.

Under this condition, we were able to prove that the time-limit of the mean throughput offered by the multicast group to each member of the overlay tree is given by the minimum throughput available in the TCP connections used. In particular it is constant with respect to the size and the topology of the group if the latter is homogeneous. This quite intuitive result exhibits a behaviour radically different to the behaviour of a multicast group supported by the IP-network.

Next, we studied the delay and the memory usage by relaying users. We proved that if the rate of the packets sent by the source is larger than the limiting throughput then at least one memory buffer usage grows without bound. We also proved that under certain moment conditions, and in the case when the departure rate of packets from the source is smaller than the saturating throughput rate, then the mean memory buffer usage of a relaying user is finite regardless of the number of transmitted packets and the position of the relaying user on an infinite multicast tree.

In particular, the mean memory required can be explicitly expressed as the Legendre transform of a certain hydrodynamic limit in a percolation model (similarly as in [32]). The numerical evaluation of this transform gives values very close to those obtained by a simulation.

All these results are the subject of a common publication [18] with the research group "Systems and Optimization" from the Watson T.J. laboratory at IBM. It will be presented at the IEEE Infocom 04 conference.

6.1.5. Control theory for TCP flows

6.1.5.1. Design of feedback controls supporting TCP

Since end-users of an IP network do not know what capacity they can be allocated, they require a dynamic window-based mechanism like TCP which provides some feedback information about congestion. However, existing AQM (active queue management) schemes have not focused on the kind of control structures that are necessary to control such closed-loop systems. In addition, they do not consider how to compensate for delays. This is unfortunate because delay-independent control has limited performance in the presence of large delays.

In [25][15][17][16][24], we addressed these issues based on modern control theory as follows.

- We proved that in order to fully support TCP, we need a PD-type (Proportional-Derivative) state-feedback control structure in terms of queue length (or RTT: Round Trip Time) which backs up the conjecture in the networking literature that the AQM RED is not enough to control TCP's dynamic behavior. RED can be classified as a P-type AQM (or as an output feedback control for the AIMD model);
- In order to fully support TCP in the presence of delays, we derived delay-dependent feedback control structures using the knowledge of RTT, capacity and number of sources. This is new compared to existing AQM schemes such as RED, REM/PI and AVQ which are all delay-independent controls;
- In order to interpret different AQM structures in a unified manner rather than to compare them via simulations, we proposed a PID-type mathematical framework using an integral control action.

As a performance index to measure the deviation of the closed-loop system from equilibrium, we used a LQ (linear quadratic) cost of the state and control variables such as queue length, aggregate rate, jitter in the aggregate rate and congestion measure. Stabilizing gains of the proposed feedback control structures are obtained by minimizing the LQ cost. Then, the impact of the control structure on performance is analyzed from the study of the stabilizing gain design for the proposed mathematical framework. All results were extended to the case of multiple links and heterogeneous delays.

6.1.5.2. Generalized receding horizon control scheme for constrained linear discrete-time systems

Receding horizon control (RHC) uses the current control law obtained by solving the optimization problem every sampling instant. Since receding horizon control can consider a finite horizon cost function, it can easily handle input/state constraints, time-varying systems, uncertain systems, etc. For this reason, it has been widely investigated in theory and in practice.

In [6][23][14], we proposed an asymptotic receding horizon tracking control (RHTC), a generalized stabilizing RHC and receding horizon H_∞ control (RHHC) schemes for input/state constrained linear discrete time-varying systems, that are better than existing schemes in terms of feasibility and on-line computation in the constrained finite-horizon optimization problem. The control schemes are based on a time-varying horizon cost function with time-varying terminal weighting matrices, which can easily be implemented via a linear matrix inequality (LMI) optimization.

6.2. Modeling of cellular and ad hoc wireless networks

Key words: *CDMA/UMTS*, *ad hoc networks*, *IEEE 802.11*, *Hiperlan*, *CSMA*, *MAC protocols*, *signal to interference ratio*, *coverage*, *capacity*, *admission and congestion control*, *transport capacity*, *spatial modeling*, *stochastic geometry*, *point processes*, *shot-noise*, *Boolean model*, *Voronoi tessellation*.

Participants: François Baccelli, Bartek Błaszczyszyn , Charles Bordenave, Mohamed Karray, Paul Muhlethaler, Florent Tournois, Minh Anh Tran.

This axis concerns analysis of stochastic models stemming from wireless communication, in particular in the CDMA/UMTS and ad hoc networks. Primarily, we are interested in macroscopic models, which are particularly important for the economic planning. Our approach is based on stochastic geometry.

6.2.1. Admission/congestion control and maximal load in large CDMA networks

This work is focused on the influence of geometry on the combination of inter-cell and intra-cell interferences in the downlink of large CDMA networks. We used an exact representation of the geometry of the downlink channels to define scalable admission and congestion control schemes, namely schemes that allow each base station to decide independently of the others what set of voice users to serve and/or what bit rates to offer to elastic traffic users competing for bandwidth. We studied the load of these schemes when the size of the network tends to infinity using stochastic geometry tools. By load, we mean the distribution of the number of voice users that each base station can serve and that of the bit rate offered to each elastic traffic user.

6.2.1.1. Feasibility of the downlink power control

In our approach, the localization of both the antennas and the mobiles is represented by point processes on the plane. The necessary and sufficient condition for the feasibility of the uplink and the downlink, globally in the network, is related to the spectral radius of some random, infinite matrix of the attenuations, whose entries depend on the locations of the points of both point processes. In a first article [12] we proposed a sufficient condition for the feasibility of the downlink power allocation, that is based on the sub-stochasticity of the attenuation matrix. This approach permits the analysis of the load of each base station cell in a decentralized way, considering only its own users and locations of other base stations. In certain cases, for example for the Poisson point process of antennas and mobiles, this approach gives an explicit closed form solution for the mean global capacity of the network. In particular, given the density of the base stations we found the density of the users that can be served by the network. The approach adopted in this paper leads to some decentralized admission and congestion control schemes. These protocols are subject to a pending INRIA patent.

6.2.1.2. Uplink and downlink with maximal power constraints

In the next step in [21] we extended our approach to the uplink and took into account the existence of maximal power constraints of the base stations and users. Moreover, in hexagonal network, using Gaussian approximations for the total load imposed on a given cell by all users served in it, we gave explicit formulas for the infeasibility probability; i.e., for the probability that a Poisson population of a given intensity cannot be entirely accepted by the base station running our admission control protocol. The refinement of the admission and congestion control protocols that take into account maximal base station powers and user powers in both uplink and downlink lead to two joint INRIA-France Telecom patents.

6.2.1.3. Sectorization effect

Maximal load estimation for CDMA networks where base stations are equipped with directional antennas was studied in [31]. A perfect sectorization would scale up the maximal load of the network by the number of sectors. However cross-sector interference in real network reduces this effect. We quantified this effect using our decentralized approach.

6.2.1.4. Macrodiversity

We extended our mathematical model of CDMA networks to a model where the base stations are jointly encoding and decoding signals. This kind of cooperation between base stations is called macrodiversity. On the downlink, mobiles are receiving a signal from several antennas and on the uplink, mobiles are sending a signal which is received by several antennas. The gain obtained with macrodiversity is still an open issue and no admission control protocol has been proposed for these networks.

For the downlink, our mathematical model is an extension of the model developed in [12]. A necessary and sufficient condition and a necessary condition for the feasibility of our model have been deduced from our previous results. These conditions are difficult to handle since they are expressed in terms of a complex minimization problem. However, they allowed us to give some characterizations of the optimal power allocation. In particular, we have proved that the number of mobiles receiving a signal from more than two different antennas is bounded above by the number of antennae.

Our focus is to extend the analytical results known in the monodiversity case ([12] and [21]) and to find a decentralized protocol leading to a near optimal power allocation.

6.2.2. Mobile ad Hoc Networks

The exact representation of signal to interference ratio based on stochastic geometry has shed light on two problems of central importance in MANETs

- connectivity, most often analyzed under (over)simplified Boolean model representations, is in fact not always improved by densification as recently shown with O. Dousse and P. Thiran of EPFL;
- MAC protocols can be optimized for maximizing the network total transport capacity as shown via a collaboration with P. Muhlethaler of Hipercom that is again based on additive and maximal shot noise representations of interferences.

6.2.2.1. Connectivity in MANETs

In the paper [13], we studied the impact of interferences on the connectivity of large-scale ad-hoc networks using percolation theory. We assumed that a bi-directional connection can be set up between two nodes if the signal to noise ratio at the receiver is larger than a certain threshold. The noise is the sum of the contributions of interferences from all other nodes, weighted by a coefficient γ representing an orthogonality factor and of a background noise We found that there is a critical value of γ above which the network is made of disconnected clusters of nodes. We also proved that if γ is non zero but small enough, there exist node spatial densities for which the network contains a large (theoretically infinite) cluster of nodes, enabling distant nodes to communicate in multiple hops. This paper was nominated for best paper award at Infocom 03, San Francisco and sent to the fast track for IEEE ToN.

6.2.2.2. A spatial reuse Aloha MAC protocol for multihop wireless mobile networks

We defined an Aloha type access control mechanism for large mobile, multihop, wireless networks. This mechanism is based on a representation of the interferences and hence of the collisions adapted to the context of large networks with random mobility. The mechanism is designed for the multihop context, where it is important to find a compromise between the spatial density of communications and the range of each transmission. More precisely, it is possible to optimize the product of the number of simultaneously successful transmissions per unit of space (spatial reuse) by the average range of each transmission. The optimization is obtained via an averaging over all Poisson configurations for the location of interfering mobiles. The main mathematical tools stem from stochastic geometry and are spatial versions of the so called additive and max shot noise processes. This work was presented at the Allerton conference [11].

6.3. Network dynamics

Key words: *max plus algebra*, *Lyapounov exponent*, *monotone-separable networks*, *topical function*, *sub-exponential distribution*, *sub-additivity*, *queue*, *access distribution*, *Veraverbeke's theorem*, *Jackson networks*.

Participants: François Baccelli, Marc Lelarge, Serguei Foss.

6.3.1. Heavy tail asymptotics and long range dependence

The theory of rare events for subexponential networks was developed (almost from scratch) via a 4 year long collaboration between TREC and S. Foss. Among the main results, we would quote the tail behavior of the end to end delay in max plus networks, and the tail behavior of workload in generalized Jackson networks, together with new developments on networks of the same classes based on fractional Gaussian processes.

6.3.1.1. Asymptotics of subexponential max-plus networks: the stochastic event graph case

In a joint work with Serguei Foss from Heriot-Watt University [19], we calculated the exact tail asymptotics of stationary response times for open stochastic event graphs, in the irreducible and reducible cases. These networks admit a representation as (max,plus)-linear systems in a random medium. We studied the case of renewal input and i.i.d service times with subexponential distributions. We showed that the stationary response times have tail asymptotics of the same order as the integrated tail of service times. The mutiplicative constants only involve the intensity of the arrival process and the (max,plus)-Lyapunov exponents of certain sequences of (max,plus)-matrices associated to the event graph.

6.3.1.2. Tails in generalized Jackson networks with subexponential service distributions

In the case of generalized Jackson networks, we focused on a key state variable, already used in the past for determining the stability region of such networks [35], which is the time to empty the network when stopping the arrival process. We studied the case of renewal input, Markovian routing and i.i.d. service times with subexponential distributions. In a joint work with Serguei Foss [38], we derived the exact asymptotics for the tail of this state variable in the stationary regime.

6.3.1.3. Asymptotic tail distribution of end-to-end delay in networks of queues with self-similar cross traffic

In a joint paper with Zhen Liu and Cathy Xia from IBM T. J. Watson Research Center [26], we considered the steady state distribution of the end-to-end delay of a tagged flow in queueing networks where the queues have self-similar cross traffic. We assume that such cross traffic at each queue, say queue i, is modeled by fractional Brownian Motion (FBM) with Hurst parameter $H_i \in [1/2, 1)$, and is independent of other queues. The arrival process of the tagged flow is renewal. Two types of queueing networks were considered. We showed that the end-to-end delay of the tagged flow in a tandem queueing network, and more generally in a tree network, is completely dominated by one of the queues. The dominant queue is the one with the maximal Hurst parameter. If several queues have the same maximal Hurst parameter, then we have to compare the ratio $\frac{(1-\rho)^H}{\sigma}$ to determine the dominant queue, where ρ is the load of the queue. In the case where the tagged flow is controlled through a window based congestion control mechanism, the end-to-end delay is still asymptotically Weibullian with the same shape parameter. We provided upper and lower bounds on the constant that determines the scale parameter of the corresponding Weibull distribution.

6.3.2. Fluid limit of generalized Jackson networks

In [44], we used a sample-path technique to derive asymptotics of generalized Jackson queueing networks in the fluid scale, namely when space and time are scaled by the same factor n. The analysis presupposes only the existence of long-run averages and is based on some monotonicity and concavity arguments for the fluid processes. The results provide a functional strong law of large numbers for stochastic Jackson queueing networks since they apply to their sample paths with probability one. The fluid processes were shown to be piece-wise linear and an explicit formulation of the different drifts is given. In particular, this fluid limit gives a simple computation of the constant $\gamma(0)$ that appears in the stability condition for such networks as demonstrated in [34].

6.4. Stochastic geometry and point processes

Key words: *Bartlett spectral measure*, *Hawks process*, *Voronoi tessellation*, *spatial point process*, *non-homogeneity*, *double-stochastic Poisson Process*, *boolean model*, *approximations*.

Participants: Pierre Brémaud, Bartek Błaszczyszyn , Emmanuel Roy, René Schott, Andréa Ridolfi, Laurent Massoulié.

This year our works are focused on spectral analysis of point processes and approximations of non-homogeneous Voronoi tessellations, and percolation.

6.4.1. Second order properties of random fields of point processes

This axis concerns spectral analysis of processes related to point processes: random sampling processes, shot noises, and the point processes themselves, for example Hawkes processes or point processes with clusters. In [40][39][41] we have presented general formulas for Cramer or Bartlett power spectral measures with respect to a point process that is not necessarily a Poisson, renewal, or Cox, but a general stationary point process whose Bartlett spectrum is known. Such a generality is needed in many circumstances. For example, using the results of this basic theoretical research, in [42], we present the calculation of the spectra of complex signals used in ultra-wide bandwidth.

6.4.2. Representation of point processes admitting exvisible intensities

For his PhD, Emmanuel Roy has investigated the representation of a point process admitting an exvisible intensity (also called Panpagelou intensity). His aim was to extend a result known for Point processes on

the real line admitting a previsible intensity: such a process is obtained by projection of the points of a homogeneous Poisson process (on the half-plain) that occur below the graph of the intensity.

6.4.3. Approximate decomposition of some modulated-Poisson Voronoi tessellations

Approximate decomposition is a technique of the approximation of the inhomogeneous models by the results obtained for the homogeneous ones. Mathematical formalization of this technique requires estimations of the errors of approximation.

In [7] we considered the Voronoi tessellation of Euclidian space that is generated by an inhomogeneous Poisson point process whose intensity takes different constant values on sets of some finite partition of the space. Considering the Voronoi cells as marks associated to points of the point process, we prove that the intensity measure (mean measure) of the marked Poisson point process admits an approximate decomposition formula. The true value is approximated by a mixture of the respective intensity measures for homogeneous models, while the explicit upper bound for the remaining term can be computed numerically for a large class of practical examples. By the Campbell formula, an analogous approximate decomposition was deduced for the Palm distributions of individual cells. This approach makes possible the analysis of a wide class of non-homogeneous-Poisson Voronoi tessellations, by means of formulae and estimates already established for homogeneous cases. Our analysis applies also to the Poisson process modulated by an independent stationary random partition, in which case the error of the approximation of the double-stochastic-Poisson Voronoi tessellation depends on some integrated linear contact distribution functions of the boundaries of the partition elements.

7. Contracts and Grants with Industry

7.1. CRE with France Télécom R&D

Participants: François Baccelli, Bartek Błaszczyszyn , Jean-Marc Kelif, Mathieu Monfalet, Minh Anh Tran.

Contrat de recherche externalisée (CRE) with France Télécom R&D (represented by Jean-Marc Kelif and Mathieu Monfalet) entitled “Strategies for the densification of the UMTS network” was signed and realized in 2003.

Tools of FT R&D allow to dimension UMTS networks by means of simulations. The study proposed in the CRE (whose extension is taken into account) consist in developing a new analytical approach based on the stochastic geometry models developed by TREC (see section 6.2.1). The main activities in 2003 were:

- the adaptation of the developed model, in particular integrating signal propagation characteristics used by FT R&D in the case of omnidirectional and directional antennas,
- a partial validation of the model by the comparison of the analytical results to the simulations performed by FT R&D

Preliminary validation results, presented in [29], justify the proposed methods.

7.2. Opération Stratégique Conjointe with Alcatel Bell " End-to-end performance evaluation of packet communication networks

Participants: François Baccelli, Augustin Chaintreau, Danny De Vleeschauwer, Dohy Hong, Ki Beak Kim, David Mc Donald, Guido Petit, Julien Reynier.

This project proposes to develop a general methodology for the analysis of the end to end behavior of key IP applications, including both TCP and UDP applications over large networks.

The main scientific questions concern the evaluation/prediction of the end to end performance (mean values and fluctuations of throughput, delay and loss) obtained by individual TCP controlled (resp. UDP) applications

under various potential access modes: xdsl, wireless, optical burst etc. and under various IP backbone loading assumptions.

The proposed research contains :

1. A statistical part, which is only partially done, and which bears on the identification of the so called potential traffic of key IP applications including emerging applications such as TCP controlled audio-video data sharing and UDP video streaming; this will allow one to identify generic models for these applications and to build traffic generators to be used in simulations.
2. A performance evaluation part, which bears on the end to end analysis of mixes of TCP controlled applications and UDP applications within the setting of large IP networks involving various types of access technologies and various types of backbone architectures; the central question within this setting is the evaluation of the individual throughput obtained by an application when it shares the local loop and the backbone with a large number of other applications.

The current activities contain several subprojects:

- Analytical models for flow and congestion control over large IP networks for the Network Strategy Group of Alcatel. This resulted in the hiring by TREC of 3 temporary engineers each over 1 year: A. Chaintreau, J. Reynier and K.B. Kim, in a series of 8 joint papers and in an internal workshop organized for Alcatel at corporate level.
- Consultancy studies for the Broadband Access Business Unit of Alcatel Bell: three studies were completed, all on DSL architectures.
- The new N2N simulation tool developed by TREC for the simulation of large IP networks was used to develop two simulation softwares for the DSL architectures of Alcatel. The transfer of these tools to Alcatel is currently being finalized through the N2NSoft project led by D. Hong.
- The analysis of load balancing strategies in core networks, started in 2003 with Alcatel Marcoussis.

Several specific access and core technologies have been studied:

- DSL access networks [8] presented at Infocom 03;
- OBS core networks [10] presented at ITC 03;
- Load balancing in core networks, ongoing research with Marcoussis;
- Wireless access networks [20], to be presented at Infocom 04.

Generic interaction models were shaped for various types of applications and control mechanisms:

- Long lived flows, presented at Infocom 02 [36] and Performance 02 [43];
- On-Off flows, submitted to ACM Sigmetrics [33];
- AQM schemes such as RED, see [24] and [37], presented at Performance 02;
- Several Bottlenecks, presented at Infocom 03 [9].

The first 2 year phase of this comprehensive research program is now completed. This OSC had a major impact on all aspects of our activity, from theoretical research (5 theoretical papers of TREC stem indirectly from the OSC), to the ongoing transfer project. We are currently working on the elaboration of a second phase with Alcatel's Network Strategy Group so as to implement a common network engineering methodology across several Business Divisions and corporate functions within Alcatel.

7.3. IBM Academic Award on Overlay Multicast and Web Computing

Participants: François Baccelli, Augustin Chaintreau, Marc Lelarge.

TREC was awarded an IBM Academic Award to work on overlay multicast and web computing. This renewable award was granted for 2003 in relation with the collaboration with the group of Z. Liu of IBM Research, T.J. Watson center, Hawthorne NY. Three joint technical reports have been prepared on the matter: [18], which bears on the infinite memory case, will be presented at Infocom 04 in Hong Kong; [26], which bears on the case with self similar cross traffic, will also be presented at Infocom 04; a third paper on the case with backpressure is currently being completed.

A prototype was designed and tested. An IBM patent (with 2 INRIA co-authors) was filled. The joint research programme includes the exchange of two PhD students (A. Chaintreau and M. Lelarge).

8. Other Grants and Activities

8.1. Networks and international working groups

- TREC was a partner in the INTAS European Project "Asymptotics of Stochastic Networks" with IPIT (Moscow), the universities of Novosibirsk, Cambridge, Ulm, Lund, and Patras that ended in 2003.
- F. Baccelli is a member of the IFIP W.G. 7.3. work group and a member of the scientific committee of the department of « Stochastic Networks » in Eurandom center in Eindhoven.
- TREC is a partner in ARC TCP, which includes the Mistral, Armor, Planete and Hipercom project teams of INRIA and other partners like FT R&D, EPFL. TREC coorganized a workshop on the matter at ENS in November 2003.
- TREC is a partner in the new European Network of Excellence (NoE) called EuroNGI led by Groupement des Ecoles des Télécoms (GET). TREC will be the coordinator of the INRIA participation to this NoE. The kick off meeting of this NoE took place in December 03.
- TREC participates in the AS Informatique et Systèmes Dynamiques.

9. Dissemination

9.1. Animation of the scientific community

9.1.1. Invited scientists

9.1.2. Professor David McDonald

is on sabbatical leave from the University of Ottawa from June 30, 2003 until July 1'st, 2004. He has been a member of TREC since September 1'st 2003 and will continue in that capacity until July 1'st, 2004.

9.1.3. TREC's seminar

the following visitors gave talks:

- France
  - Thierry Bousch (PARIS Vll, LIAFA), Mach 2003
  - Paul Muhlethaler (INRIA Rocquencourt), May 2003,
  - Huu Quyn Nguyen (Ecole Polytechnique, Purdue University intern), August 2003,
  - Tran Minh-Anh (Ecole Polytechnique, INRIA-TREC intern) September 2003,
  - Dao Ha (Ecole Polytechnique, INRIA-TREC intern) September 2003,

  - Chadi Barakat (INRIA Sophia Antipolis), November 2003,

- Europe

  - Tomasz Rolski (Wroclaw University, Poland), January 2003,
  - Serguei Foss (Heriot-Watt University, Edinburgh), March 2003,
  - Olivier Dousse (EPFL, Lausanne), June 2003,
  - Takis Konstantopoulos (University of Patras, Greece), July 2003,
  - Giovanna Nappo (University of Roma, La Sapienza, Italia), September 2003,
  - Takis Konstantopoulos (University of Patras, Greece), November 2003,

- America and Asia

  - Ki Baek Kim (CALTECH, USA), March 2003,
  - Song Chong (KAIST Taejon, Korea), May 2003,
  - Ravi Mazumdar (School of Electrical and Computer Engineering, Purdue University, USA), July 2003,

9.1.4. Miscellaneous

- D. Hong animates the project-team seminar: http://www.di.ens.fr/~trec/seminaire.html
- P. Brémaud is a member of the editorial board of the following journals: *Journal of Applied Probability, Advances Applied Probability, Journal of Applied Mathematics and Stochastic Analysis*;
- F. Baccelli is a member of the editorial board of the following journals: *QUESTA, Annals of Applied Probability, Markov Chains, Mathematics of Operations Research* and *Journal of Discrete Event Dynamical Systems*. He was a member of the program committee of the following conferences: Infocom 03 (San Francisco), WiOpt 03 (Sophia Antipolis), ARC TCP 03 (Paris) and "Colloques des usages de l'Internet" (Nice). He coorganized the Oberwolfach seminar held in December 03 on applied probability and stochastic networks jointly with A. Hordijk and V. Schmidt. F. Baccelli maintains a web-page on stochastic geometry for communications http://www.di.ens.fr/~trec/sg

9.2. University teaching

Dept. of Mathematics, University of Rome, La Sapienza Mini-course on Point Processes (P. Brémaud, June 2003)

DEA Probabilités, Paris 6 Graduate Course on Queueing Theory in collaboration with J. Mairesse and L. Massoulié (40h).

Ecole Normale Supérieure, MMFAI Course on Information Theory. of P. Brémaud and M. Lelarge (36h). Undergraduate course (master level) of F. Baccelli and Marc Lelarge on Communication Networks (36H). Undergraduate course (master level) of F. Baccelli, P. Brémaud, J.F. Le Gall and C. Bordenave on applied probability (48h).

9.3. Invitations and participation in conferences

F. Baccelli

- Presentations at the following conferences
  - Schroedinger Institute, conference on idempotent mathematics, Vienna, February 03.
  - Infocom 2003, San Francisco, USA, April 2003, http://www.ieee-infocom.org/2003/,
  - WiOpt, INRIA Sophia-Antipolis, March 2003,
  - Algotel 03, Banyuls (invited lecture) May 2003,
  - Allerton Conf. on Communication, Allerton USA, October 2003 (invited lecture),
  - MICS Conference, Monte Verita, Switzerland, October 2003 (invited lecture), http://www.mics.org,
  - INRIA Evaluation of TREC, Jouy-en-Josas, October 2003,
  - SAMSI workshop on Internet Traffic, Research Triangle, North Carolina, October 2003 (invited lecture),
  - ARC-TCP, Paris, November 2003.
- Presentations at the following seminars
  - EPFL, on the Billiard TCP model, March 03.
  - Berkeley, on stochastic geometry, April 03.
  - Caltech, on CDMA, April 03.
  - University of Maryland, on MANETs, April 03.
  - ETH, on wireless networks, May 03.
  - Porquerolles seminar on ad hoc networks, September 03.
  - Purdue University, USA, October 2003,
- PhD thesis committees:
  - A. Proutière [30].
  - K. Kofman (HDR).
- Others:
  - Member of the NSF ITR pannel, Washington DC, January 03.
  - Reviewer of the Metropolis RNRT project.

B. Błaszczyszyn

- Presentations at the following conferences
  - Infocom 2003, San Francisco, USA, April 2003, http://www.ieee-infocom.org/2003/,

  * WiOpt, INRIA Sophia-Antipolis, March 2003,
  * Workshop on Applied Probability and Advanced Communications Networks, Bedlewo, Poland, May 2003,
  * INRIA Evaluation of TREC, Jouy-en-Josas, October 2003,
  * Oberwolfach Meeting on Applied Probability, Oberwolfach, Germany, December 2003.

- Participation at the following conferences

  * MICS Conference, Monte Verita, Switzerland, October 2003, http://www.mics.org.

A. Chaintreau

- Presentation at the following seminar

  - IBM Watson T.J. Seminar, August 2003.

D. Hong

- Presentations at the following conferences:

  * Infocom 2003, San Francisco, USA, April 2003, http://www.ieee-infocom.org/2003/,
  * INRIA Evaluation of TREC, Jouy-en-Josas, October 2003,
  * 1st Workshop France-Korea on ITC, Daejun, KOREA, September 2003

- In July 2003, Dohy Hong was awarded the ANVAR national prize for the creation of the N2NSoft Startup.

K.B. Kim

- Member of the program committee of the ICC 2003 - Communication QoS, Reliability, and Performance Modeling,
- Presentations at the following conferences:

  * IEEE American Control Conference, Colorado, USA, June 2003.
  * ARC-TCP, Paris, France, November 2003
  * IEEE Globecom, San Francisco, USA, December 2003.
  * IEEE Conference on Decision and Control, Hawaii, USA, December 2003.

- Participation at the following conference

  * DISC Summer School on Modeling and Control of Hybrid Systems, Veldhoven, Netherlands, June 2003.

- Presentations at the following seminars:

  * ENS-DI (Séminaire TREC), Paris, March 2003,
  * Alcatel, Brussels, Belgium, September 2003,
  * ICSI-Berkeley (Sally Floyd), San Francisco, December 2003,

* IBM T. J. Watson Research Center (Zhen Liu), Yorktown Heights, December 2003.

D. McDonald

– Presentations at the following conferences

* ARC-TCP: Models and algorithms for TCP/IP Networks, Paris, November 2003.
* Oberwolfach Meeting on Applied Probability, Oberwolfach, Germany, December 2003.

M. Lelarge

– Presentations at the following conferences

* Workshop on Applied Probability and Advanced Communication Networks, Bedlewo, Poland, May 2003,
* ARC-TCP: Models and algorithms for TCP/IP Networks, Paris, November 2003.

J. Reynier

– Presentation at the following conference

* International Teletraffic Conference, Berlin, September 2003.

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