Application

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Information about application

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Descriptive data

Project info

Project title (Swedish)*

Latenskontrollerade nätverk

Project title (English)*

LAtency-Controlled NETworking (LACNET)

Abstract (English)*

We propose a novel view of latency and delay control in communication networks with emphasis on wireless systems. We consider the new concept of age of information as the central measure of latency and combine it with the use of flexible and adaptively determined expiration deadlines for the messages, in order to control, reduce, and minimize the overall tardiness in delivering information. We also propose a new approach to the resource allocation problem in wireless networks, which is known as scheduling, and include the idea of using metadata as a means of protecting the content of sensitive messages as we manipulate their age, deadlines, and transmission schedules. The age measure is coupled with signal sparseness and compression as it depends on signal autocorrelation properties and leads to the concept of effective age. The deadline control is based on age status and results in soft, dynamically controlled expiration times. Such use of deadlines is totally new and provides a flexible way of delay control. The scheduling problem is formulated in a way that impacts the fundamentals of optimization theory and leads to cross-layer solutions that minimize total delay by minimizing service time. Finally, the use of metadata leads to communication complexity trade-offs since it is an alternative to the use of a secure channel.

Popular scientific description (Swedish)*

När informationsteknologin får ett allt starkare grepp om vår vardag och vi i allt större utsträckning förlitar oss på Internet och trådlös kommunikation för fler och fler applikationer, blir fördröjningen i elektroniska tjänster kritisk. För tillämpningar såsom övervakning, miljöstyrning, inhämtning av data från sensorer, nödtjänster, medicinska varningar, etc. är det av största vikt att meddelandefördröjningen minimeras. Olyckligtvis gör komplexiteten i dagens kommunikationsnätverk, speciellt trådlösa nätverk, att analysen av fördröjning i nätverken blir extremt svår. I detta projekt introducerar vi fyra innovativa metoder för att göra ett genombrott inom fördröjningskontroll i kommunikationsnätverk.

Den första är relaterad till "åldern" eller färskheten hos den utsända informationen. När en fysisk process övervakas skickas uppdaterade mätningar av dess värde, men de förlorar sin färskhet hos mottagarna tills uppdaterade mätningar tas emot. Vi föreslår nya metoder för att utvärdera åldern på meddelanden samt kontrollera den.

Den andra involverar ett nytt sätt att implementera ”tidsfrister”. En etablerad metod för kontroll av tidskritiska nätverk använder tidsfrister kopplade till meddelanden så att de förkastas om meddelandet inte når sin destination innan tidsfristen löpt ut. Vi föreslår adaptiva metoder för att sätta och uppdatera tidsfristerna som även bygger på åldern av meddelandet.

Den tredje metoden attackerar direkt allokeringen av resurser för transmission, känd som ”schemaläggning” inom kommunikationsnätverk. Vi utnyttjar idén att den totala fördröjningen är en ökande funktion av tiden att behandla ett meddelande. Därav, genom att minimera behandlingstiden för meddelanden kommer vi också minimera den totala fördröjningen. Vi kan lösa minimeringsproblem för behandlingstiden av meddelanden mycket lättare än att direkt försöka minimera den totala fördröjningen. En specifik instans av detta angreppssätt är kopplad till att tömma ett system av buffrad data på minimal tid. Detta problem kan lösas med vårt angreppssätt.

Slutligen, den fjärde metoden är kopplad till ett speciellt skydd av innehållet i känsliga meddelanden när vi försöker kontrollera fördröjningen. Detta åstadkommer vi med hjälp av metadata som gömmer och skyddar meddelandeinnehållet.

Alla fyra komponenterna i detta projekt är starkt sammankopplade och erbjuder nya och lovande metoder för att kontrollera fördröjningen i kommunikationsnätverk. Effekten kommer bli signifikant för det stora antal tjänster som är tidskritiska och är beroende av transmission av meddelanden i nätverk och trådlösa kanaler.

Project period

Number of project years*

3

Calculated project time*

2016-01-01 - 2018-12-31

Classifications

Select a minimum of one and a maximum of three SCB-codes in order of priority.

Select the SCB-code in three levels and then click the lower plus-button to save your selection.

SCB-codes*	2. Teknik > 202. Elektroteknik och elektronik > 20204. Telekommunikation
	2. Teknik > 202. Elektroteknik och elektronik > 20203. Kommunikationssystem
	2. Teknik > 202. Elektroteknik och elektronik > 20202. Reglerteknik

Enter a minimum of three, and up to five, short keywords that describe your project.

Keyword 1*

wireless networking

Keyword 2*

adaptive deadline control

Keyword 3*

wireless scheduling

Keyword 4

delay

Keyword 5

network control

Ethical considerations

Specify any ethical issues that the project (or equivalent) raises, and describe how they will be addressed in your research. Also indicate the specific considerations that might be relevant to your application.

Reporting of ethical considerations*

Not Applicable.

The project includes handling of personal data

No

The project includes animal experiments

No

Account of experiments on humans

No

Research plan

I. PURPOSE AND AIMS

We propose a far-reaching set of ideas for the control of network delay with special focus on dynamic wireless networks. These ideas use the new concepts of **age of information** and **adaptive deadline control**, as well as an innovative approach to the **wireless scheduling** problem. They aim at overcoming the roadblock of delay calculation in such networks and, at the same time, to contribute to the theory of optimization and network science. Furthermore, the use of **metadata concepts** is proposed to permit the implementation of these techniques for encrypted and sensitive data. Despite the progress made in the study of wireless networks (especially those that operate in highly dynamic and threat-prone environments), the major challenge of tracking, controlling, and optimizing latency remains unresolved. In fact, the community uses the oxymoron term "delay-tolerant", almost euphemistically, to describe such networks, as an admission of its inability to effectively control delay. When the missions served by a deployed wireless network are time-critical, it is clear that the issue of latency and delay control must be at the top of the agenda.

This is a resubmission of a proposal submitted in 2014. Since that time considerable progress has been made in already advancing the aims of the proposal. New results, new team composition, and a refocused project description have improved the proposal significantly, including its feasibility. Most importantly, the novelty and the visionary character of the proposal are now better explained.

In this proposal we outline four novel ways in which we propose to address the objective of effectively handling delay or, more importantly, the broader concept of latency.

1. We propose a method for tracking and controlling the transmission of "updates" in cases where the traffic is generated from sources that observe on-going processes (as in surveillance, market and environmental monitoring, threat detection, etc.). The key component of our approach is to track the "age" of the transmitted observation and then control that age via adaptive methods that decide when to transmit new updates and when to discard "old" messages. In a wireless environment, this issue is complicated by channel conditions and other-user behavior. Taking into account the effects of the wireless medium is an essential part of our approach, although the "age" concept is equally well applicable to all networks. Note that although age is affected by delay, it is not synonymous with it. This concept is totally new and fundamental for securing the timeliness and freshness of information. It should be pointed out that it has emerged as a focus area for the National Science Foundation (NSF)'s research programs in the United States. This occurred recently in a workshop sponsored by NSF and attended by the PI.

2. The discarding of useless messages is an established means for reducing the traffic load on any kind of network. In fact this objective is consistent with the minimization of age of received information, as obsolete packets may be occupying network resources while having been overtaken by fresher ones. An effective means for modeling the discard process is via the use of deadlines. That is, every message carries a deadline, which helps to prioritize, delay, or discard it. What we propose here is to introduce the concept of "soft" or adaptive deadlines. That is, convert the deadline assignment process into a dynamic one, whereby every packet's priority status is constantly under reconsideration. Again, the wireless environment introduces complications but also opportunities for controlling these deadlines, since additional control levers (such as interference control and channel state information) are available. Note that there is a strong connection of this new take on deadlines with the concept of "age" described above. Specifically, age of a packet can be used as a means for deciding how to modify its expiration deadline.

3. Scheduling the transmissions of links that share a common channel is perhaps the oldest and most important problem in wireless networking. Yet, it remains largely unresolved. Especially for the case where the objective is to reduce and minimize delay, the complexity of analyzing interacting queueing models has been a roadblock in tracking delay. In addition, the variability of the

transmission rates (based on which links are scheduled to transmit simultaneously) has further hampered this effort. In this proposal, we bypass the need to compute queueing delay. As noted above, we observe that in ANY service system, the queueing delay is a convex increasing function of the service time. Hence, if we focus on minimizing the service time we also minimize delay. Tracking the service time is feasible and in the scheduling problem it corresponds to the surrogate problem of minimizing the time it takes to empty a network from an initial traffic volume without new arrivals. We propose to address this problem in a totally innovative way that has the unique feature that it can simultaneously optimize the choice of transmission rates. We have extended our approach to this problem in a new way by focusing on how to empty the network so that the average age of the received packets is minimized. In this formulation, every packet carries a time stamp of its generation time so as to make the age minimization feasible.

4. Finally, in implementing latency control techniques, we need to consider the case of sensitive information and, hence, its protection when decisions on age and deadline are made to decide its fate. Thus, if the messages are of high security designation ("red" messages), it will be necessary to map them through the use of a metadata protocol to unsecured packets ("black" packets), which will represent their "age", delay, deadline value, etc. and, hence, will be handled openly along with regular messages without compromising their content.

II. SURVEY OF THE FIELD

We review below the proposed concepts and ideas and outline the related state-of-the-art.

II.1. Age of Information

The need for real-time status updates in an increasingly ubiquitous connectivity environment is recognized in [1], in which a new metric, called the status update age, has been defined. Status updates are periodic messages that are generated by a source, such as a sensor, in order to convey the current state of a measurement or observation. In commercial applications, these can include but are not limited to environmental sensing data [2], vehicular sensor measurements [3], etc. While real-time status updating has become increasingly popular in commercial applications fueled by the explosion of portable devices, such status update messages have been commonplace in military applications in the form of blue force tracking [4], telemetry data etc., and more recently cooperative spectrum sensing applications [5]. In such systems the status update age of a message can be loosely defined as the duration between the time of observation at the destination (of the most recent status value) and the time at which that particular update value was originally generated at the source. These messages may contain individual measurements or observations, or sometimes a collection of measurements and/or observations can be aggregated into a single packet, especially if they are required to reach a common destination.

Clearly, generating too frequent updates results in heavily loading the network and causing long delays due to congestion and, at the same time, causing disruption in the order in which the updates are received, thereby distorting their timeliness value. On the other hand, very sparse updates leave wide gaps between the updates, thereby leaving the receiver with ageing information for long time intervals. Thus, determining the optimal rate of updates is essential for maintaining at the destination fresh information about the observed process. It is also important to utilize the correlation between successive observed samples of the process in order to compress the transmitted updates without detrimental effects on the timeliness of the knowledge at the receiver. the difficult to compute queueing delay just by minimizing service time), similarly the age of information can be minimized by minimizing the age of updates.

The concept of "age" is novel and far-reaching and is being recognized as such in the international community.

II.2. Deadlines

The use of deadlines for discarding tardy or obsolete packets has been considered from the early days of networking. For example, in scheduling packet transmissions, it was proven that the policy of scheduling the packet with the earliest deadline first (known as the EDF policy) minimized the average number of packets that did not meet their deadlines regardless of the arrival pattern of the packets at the transmission scheduler [6, 7]. However, in our context, the problem is different. We are concerned with ensuring information freshness; hence, the use of a deadline will serve the purpose of deciding that a fresher packet has "overtaken" the attempted delivery of an older packet. Therefore, the deadline should not be set at the outset and be "hard" and unchangeable. Rather, it should be a "soft" deadline that gets updated with time as conditions evolve. In fact, deadlines should depend on the intrinsic autocorrelation and information structure of the process. Thus, the deadline values become important control and design parameters to ensure the desired low latency and constitute a totally new way for dynamic network control.

II.3. Scheduling

As mentioned earlier, scheduling transmissions in a wireless network remains a fundamental cornerstone problem for operation and control in wireless environments. And since our focus is latency control, we noted earlier that the decoupling of this objective from the difficulties of queueing delay approaches to delay analysis can be achieved by focusing on the minimization of the service time in a general service system. In the scheduling context, this approach is enabled and facilitated if we focus on the problem of emptying a network of queues that reside at wireless transmitters and share the same channel in minimum time. This is known as the "empty-the-network" problem. In the area of scheduling (known also, in general, as the resource allocation problem) there has been a huge volume of work. However, there has been no final solution and none of the prior work has followed the approach we developed in our work.

In [8], we considered a set of transmitter-receiver pairs, or links, that share a wireless medium, and addressed the problem of emptying backlogged queues with given initial size at the transmitters in minimum time. The problem amounts to determining activation subsets of links, and their time durations, to form a minimum-time schedule. In that work, we presented fundamental insights and solution characterizations that included: (i) showing that the complexity of the problem remains high for any continuous and increasing rate function,(ii) formulating and proving sufficient and necessary optimality conditions of two baseline scheduling strategies that correspond to emptying the queues using "one-at-a-time'' or "all-at-once'' strategies, (iii) presenting and proving the tractability of the special case in which the transmission rates are functions only of the cardinality of the link activation sets. We then developed an algorithmic framework for the solution to this problem. Although the overall problem of scheduling has a long history of investigation in wireless systems, our approach in this proposal is totally new, both in terms of the methodology used, as well as in terms of the formulation and objectives which are aligned to the issue of freshness and timeliness.

II.4. Use of Metadata

An issue of concern in any information system is how to protect the identity and content of "red" (high-level secure) packets. This is especially true in our formulation as a deadline-based approach is used to control age. There are several metadata protocols and ideas that use the description of the packets, rather than the packets themselves, to ensure objectives such as differentiated service (like DSCP) or congestion notification (like ECN) in IP/TCP protocol stacks. We should note that these protocols may not be directly transferable to the specific wireless environment we consider here. Thus it will be necessary to modify them, or propose new ones, so as to mask packet identity and to separate it from its deadline and age value.

III. PROJECT DESCRIPTION

The proposed four main concepts are interconnected since the age of transmitted information and the setting of deadlines are dependent on the tardiness of service in the network, which, for the wireless case, depend chiefly on the transmission rates and the scheduling control. We claim that these three ideas will have a major impact on getting hold of the elusive issue of latency control and, hence, on the performance of such networks in fulfilling time-critical missions.

Furthermore, there are additional novel aspects of great importance that will be part of this investigation and affect its impact and usefulness. Specifically, we will address the separation of packet identity/content from its metadata description (age, deadline, tardiness), so as to enable the use of our approach in systems with multiple security levels.

Aided by our recent research over the last year we have improved considerably the focus, feasibility, and implementability of our proposed work.

III.1. Age

We will consider how age is affected by the sampling rate of the observed process and by the transmission paths that cause delay. Such paths can be modeled by queueing systems with parallel servers that correspond to the different networks over which the transmissions take place. The servers in these systems model the transmission channels and paths and can vary from simple M/M/1 to G/G/K. Since last year, we have investigated and published new results in the handling of packet management in the queues at the transmitter. That is, we have considered the case where newly generated samples do not just line up in the queue for transmission but actually replace prior obsolete packets that have not been transmitted yet [17]. Furthermore, we have shown how "age" can be used to enhance performance in systems with channel state information (CSI) [16].

An additional and very important dimension of this part of the work is the connection of the issue of age with data compression and compressive sensing. Clearly, the true age of an update may be an overestimate of its "effective" age. That is, if the observed process consists of highly correlated data, then the frequency of transmission of updates can be significantly relaxed without affecting the "freshness" of the information. In the extreme, if the observed process is a constant, the transmission of a single sample assures in perpetuity that the age of information is zero. We will investigate how a useful metric of "effective" age can be defined that takes into account the autocorrelation properties of the observed data. This effort will examine conditional entropy measures as well as other metrics based on estimation and extrapolation theoryTherefore, we will consider the correlation and sparseness properties in the sampled signal and develop the concept of "equivalent" or "effective" age, which is operationally the more significant variable for all applications.

Furthermore, as a sequel to our recent study, we will consider further the effect of age on channel state information (CSI) in wireless transmissions. This is an amazingly overdue consideration that has been neglected so far. Delayed CSI can have a huge effect on wireless link performance. However, the key parameter for that is not the delay per se but, rather, the effective age of the CSI value.

Last, but not least, we will consider multiple sources that share the same network resources and, hence, interact and affect each other's message age.

III.2. Deadlines

If the objective is to control latency and ensure the freshness of the available information at the receiver, a criterion needs to be established for discarding packets that are in transit but are the cause of congestion and consume network resources, while other packets that were generated later may have overtaken them by following independent paths in the network. A global state –based criterion would be ideal but is not practical. So, there needs to be a simple and implementable criterion, such as a deadline. The imposition of a hard deadline, especially at the time of packet generation is unreasonable and probably counterproductive. Thus, the deadline must be "adaptive", that is, it must be reconsidered at each node visited by the packet (or even while it resides in a buffer awaiting its turn). Alternatively, it may be "soft", in the sense that its value has a probability distribution. In that case, the decision to discard would be based on a statistical inference criterion. We will formulate appropriate models that capture the flexible use of deadlines in conjunction with tracking the information age of the transmitted packets.

Specifically, we will revisit the deadline concept as a criterion for dropping outdated messages. Our approach will be to consider "soft" deadlines that can be dynamically controlled. Thus, we will use the age of a packet as an input to the deadline setting algorithm so as to drop messages in an opportunistic way that takes into account the overall network conditions, rather than simply applying a strict and inflexible criterion.

The use of deadlines is also well suited to the application of our "age" criteria to the scheduling of transmission control in cognitive systems. The conventional method of assigning absolute primacy to the, "so-called", primary user has been proven to be rather simple-minded. In fact, more elaborate priority schemes that permit interference by the secondary users have been proven to lead to improved performance for BOTH primary and secondary users. In our project we will augment such schemes through the use of age and deadline values applied to BOTH the messages themselves, as well as to the corresponding CSI values.

III.3. Scheduling

To understand the double significance of the approach that we propose here, we should emphasize that the minimization of the "empty-the-network" time for fixed transmission rates results in a linear program (LP) of high dimension, the coefficients of which are the given, fixed transmission rates. To solve this LP, an effective method is the so-called "column generation" technique which is a sequential process of constantly improving the delay. Our main new idea here is to modify the column generation process at each step by changing the values of the coefficients themselves in a way that is inspired by the convergence properties of the method itself. As a result, the solution process is accelerated and, more importantly, it "kills two birds with one stone" by, at the same time, determining the optimal values of the transmission rates. In addition to achieving a major advance in the problem of scheduling time minimization, this idea is a major advance in non-linear optimization theory since it is applicable to any linear program in which the coefficients can also be optimally chosen.

Our methodology will include the choice of key control parameters (such as update generation rates and deadline adaptation for discarding) as functions of the age of the transmitted packets and the degree of correlation between the source packets. Taking into account correlations at the packet level requires extension of the ideas of data compression and source coding into the network layer.

In revisiting the scheduling problem, we will introduce the variables of age and deadlines in optimizing the resource allocation that is the essential part of the problem of scheduling transmissions. So, instead of just considering the "empty-the-network-in-minimum-time" problem, we will consider variants such as emptying the network such as the average age of the received information is minimized.

Again, in addition to the optimization theoretic issues that arise in formulating and solving such problems we will advance the very theory itself by optimally choosing the scheduling sequence AND the transmission rates involved at each stage.

III.4. Metadata

Since security is of paramount importance in network applications in general, and more so in latency control in particular, we will imbed the use of metadata in modeling and implementing the approached described in the studies of age, deadlines, and scheduling. This implies that we will use descriptors of the data (such as their age and deadline values), rather than the data itself, in making transmission and other decisions about the encrypted packets.

The main reason for incorporating this security-related dimension in our investigation is that the focus on preserving the "freshness" of information opens up new vulnerabilities in our network control and new methods of attack emerge that can undermine our objectives.

The use of metadata may have also a beneficial effect on the latency itself, on the utilization of the spectrum, and on the energy consumption. Instead of packing the control information on a header and therefore transmitting the entire packet when the objective is simply to update its age and its deadline value, it is more sensible and economical to transmit only the metadata associated with it. This possibility will be explored and exploited for improving the latency control performance of the deadline criterion.

In summary, we highlight below the novelty and value of our ideas in the proposed project:

1. The idea of monitoring, tracking, controlling, and optimizing latency via the "age of information" variable is a totally novel concept that will have long-range implications in rethinking wireless networks and systems, and, especially those that use and rely on sensors. Furthermore, it brings out the connection to data compression and the concept of "effective" age.

2. The use of adaptive deadlines in determining when to drop obsolete packets and reduce the network load and, thereby, the latency is also a novel concept that leverages existing knowledge in a new way.

3. The simultaneous optimization of scheduling time and transmission rates via a totally new change in the column generation method that solves a non-linear optimization problem in a totally new way that has much wider applicability beyond the barriers of latency control is actually a break-through idea that combines powerful optimization techniques with physical-layer-based scheduling for latency control.

4. Finally, the incorporation of metadata techniques for protecting encrypted messages in implementing latency control is an important element of the applicability of the results of this research.

III.5. Schedule/Implementation/and Project Organization

The PI is a part-time guest professor at the University of Linkoping (Norrkoping campus). He devotes 25% of his time to this position. He has established a documented productive record of successful research cooperation with his colleagues from prior VR support which has funded part of his work at LiU. He visits Norrkoping regularly and interacts with other faculty, students, and research staff, and occasionally he teaches short courses that draw students from across Sweden and beyond. At least 80% of his time involved in the guest professor position will be devoted to the proposed project. This amounts therefore to at least 20% of his total time.

This project was initially proposed last year but was not funded. In this resubmission we have strengthened the presentation of our ideas and have displayed new progress and results that we have achieved in the interim.

We expect that the publications, conference presentations, and student mentoring that will result from this work will disseminate the outcomes of the work worldwide and will increase the international visibility of this research group.

IV. SIGNIFICANCE

Delay and Latency Control remain the most important unresolved issues in Wireless Networks. The reason is the tremendous complexity of queueing analysis in systems that are "coupled" through the sharing of common channels and through the interference which results from it, as well as by the concatenation of several links (hops) on a path from source to destination. Our proposed approach which handles latency through an orderly sequence of tracking, controlling, and optimizing service times that arise from transmission scheduling and age monitoring, will make a significant contribution to cross-layer control, since it connects transmission rates with packet transmission rates. In addition, it provides a new way of network control through the combination of "age" and "deadline" for each packet.

Furthermore, the "collateral" fallout of our idea on general optimization theory should not be overlooked. The number of optimization problems in communications and networking science that result in LP's is huge. The opportunity to optimize simultaneously the coefficients of the LP opens up a huge agenda of possibilities for improved network and communication system design.

Thus the contribution to Network Science is three-fold. We provide new and insightful approaches to latency control, we solve the elusive minimum-delay scheduling problem, and we achieve true cross-layer control via innovative optimization techniques that advance the theory of optimization itself.

Finally, the implementability of our research is already demonstrated through the application of our research to CSI-based systems and cognitive networking.

V. PRELIMINARY RESULTS

We have already made significant progress in several of the directions of the proposed research.

In the area of age of information we have generalized the original simple model introduced by Yates [1] where only an M/M/1 transmission model was considered. In that work, it was assumed that the update samples are poured into a first-come, first-served queue outside the control of the transmitter and encounter a delay that is monotonically increasing with the rate of sampling according to the rules of a single exponential server queue. This model is too restrictive since sample updates can follow multiple parallel routes in a network and need not follow each other in the manner of a single stream. Thus we considered an M/M/infinity model which allows the updates to simply encounter independent delays through service in a network but no additional queuing delay due to each of them being forced to be served according to the sequence of their generation. This is also a simple model but it captures the effect of broad band availability. The downside of this model is that there are many obsolete packets that actually receive full transmission service. This is one of the reasons that we need to consider deadlines as we have proposed. This work was presented in the 2013 IEEE International Symposium on Information Theory (ISIT) [9].

Furthermore, to mitigate the effect of unlimited network resources that the M/M/infinity model implies and to still depart from the restrictive model considered by Yates, we employed the M/M/2 model, which represents a compromise between the two models. The analytical difficulty is significant but our solution has led to another paper accepted for presentation at the 2014 ISIT [10].

We have also analyzed the effect of age on CSI at the transmitter. To that effect, we have had our work accepted for presentation at the IEEE ICC conference [16] and have prepared a journal version for submission to the IEEE Transactions on Information Theory.

And, finally, we also considered the case where the transmitter maintains control of the queue into which the samples enter rather than dumping them into a system over which there is no direct control (as the previous models have assumed). This work was presented at the 2014 ISIT [11] and has been submitted for publication in the IEEE Transactions for Information Theory [17].

In Fig. 1 we show the generic layout of these models.

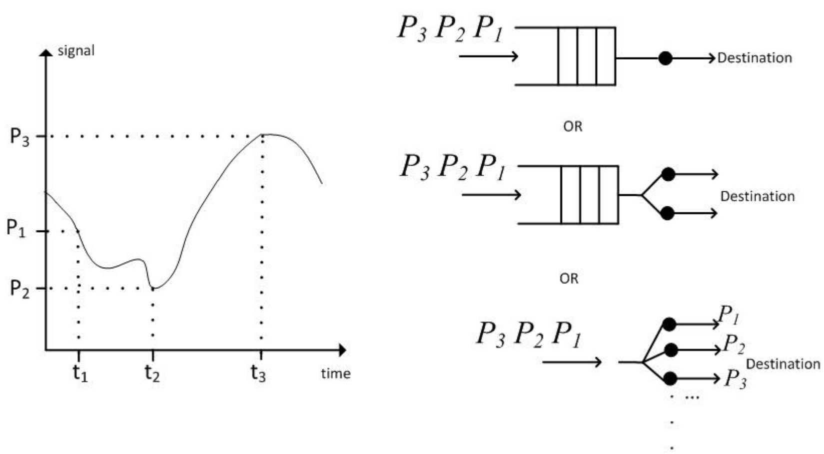

Fig 1Model Layout for the Age

In figure 2 we show how "age" evolves with time. To calculate the average age one needs to compute the area under the shown curve. This computation is a significant portion of what we have done in our investigations, so far.

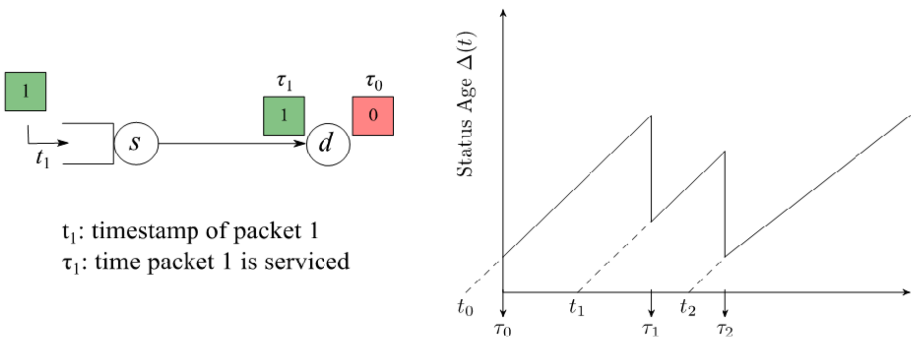

Fig 2 Age evolution with time

With respect to deadlines we have of course done pioneering work in the early days of packet switching by showing that scheduling the packet with the earliest deadline first minimizes the average number of dropped packets due to deadline expiration [6, 7]. We have also begun the formulation of such problems using dynamic deadline assignment and have started injecting the aspect of deadline into the age control and scheduling problems.

In the area of wireless scheduling, in addition to our pioneering work that led to the back-pressure algorithm, we have recently published our first collaborative work with colleagues at the Norrkoping campus of the Linkoping University in the prestigious IEEE Transactions on Information Theory [8] in which we formulated the problem of emptying a network of queues in minimum time as a linear program for which we were able to identify optimality properties of various solution strategies of low complexity. At the same time we have modeled the problem in a cross-layer fashion that allows us to also choose the transmission rates of each activated subset of queues optimally.

Specifically, if we have N terminals, each with its own queue, denoted by d_i for the $i-th$ terminal, then when we activate a set of these terminals c (for a period of duration T_i), the transmission rate of terminal i is denoted by r_{ic}.

The scheduling problem is easily shown to be equivalent to a linear program (LP). Although formulating the LP does not give a practically feasible solution algorithm, it enables us to gain structural insights. Denote by $\mathbf{T} = T_c,\ c \in \mathrm{H}$ the non-negative scheduling decision vector of dimension $2^N - 1$, whose element T_c denotes the time duration of running group $c \in \mathrm{H}$. We use $\mathbf{T}^*$ to denote an optimal scheduling solution. Notation H^* is reserved for the set of groups that correspond to an optimum solution, that is, $\mathrm{H}^* = \{c \in \mathrm{H} : T_c^* > 0\}$.

The statement of the problem is then given by

$$\begin{aligned} \min \quad & \sum_{c \in \mathcal{H}} T_c, \\ \text{s. t.} \quad & \sum_{c \in \mathcal{H}} r_{ic} T_c = d_i \quad i = 1, \dots, N, \\ & \boldsymbol{T} \geq 0. \end{aligned}$$

A rich set of results were obtained in [8]. As an example, the first step of our theoretical treatment of optimality condition, we characterize when separate link activation, in particular schedule H^1, is preferred. Intuitively, H^1 which denotes the TDMA activation pattern is desirable, if the links, when activated simultaneously with others, experience significant rate reduction. This corresponds to a high-interference environment. The following condition quantifies the notion. For all $c \in \mathrm{H}$, the sum of the ratios between the elements' rates in c and their respective rates of individual activation, is at most 1, that is,

$$\sum_{i \in c} \frac{r_{ic}}{r_{ii}} \leq 1 \ \forall \ c \in \mathrm{H}.$$

The above condition is simple in structure. Yet, it is exact in characterizing the optimality of H^1. H^1 is optimal if and only if the previous condition holds.

We have also developed low-complexity heuristics for this problem whose performance has been amply evaluated and documented and we have identified computationally tractable but optimal solutions to an important special case that arises in practice [12].

Finally, in the area of use of metadata, we have completed a significant portion of preliminary work regarding the communication complexity of using a secure channel in parallel with a public channel to counter the threat of eavesdropping. In that work, recently also published in the IEEE transactions on Information Theory [13], we calculate also the cost of energy and delay in order to achieve the desired level of content protection.

Other related studies that impact the proposed work include the consideration of cognitive systems and the impact of the availability of CSI with or without delay and with or without errors (see [14, 15, 16].

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2. A. Lindgren, C. Mascolo, M. Lonergan, R. McConnell, "Seal-to-seal: A Delay-tolerant Protocol for Contact Logging in Wildlife Monitoring Sensor Networks", Proc. Of Mobile ad Hoc and Sensor Systems (MASS), Atanta, GA, Oct. 2008, , pp. 321-327
3. N. Haddadou, A. Rachedi, Y. Ghamri-Doudane, "Advanced Diffusion of Classified Data in Vehicular Sensor networks", Proc. International Wireless Communication and Mobile Computing Conference (IWCMC), July 2011, pp. 777-782
4. K. Chevli, P. Kim, A. Kagel, D. Moy, R. Pattay, R. Nichols, A. Goldfinger, "Blue Force Tracking Network Modeling and Simulation", Proc. IEEE MILCOM, Oct. 2006, pp. 1-7
5. J-W. Yao, K-C. Leung, V. Li, " A Random Censoring Scheme for Cooperative Spectrum Sensing", Proc. IEEE GLOBECOM, Dec. 2011, pp. 1-5
6. P. Bhattacharya, A. Ephremides, "Optimal Scheduling with Strict Deadlines", IEEE Trans. On Automatic Control, July 1989, pp. 721-728
7. A. Faridi, A. Ephremides, "Distortion Control for Delay-Sensitive Sources", IEEE Trans. On Information Theory, 2007
8. V. Angelakis, A. Ephremides, Q. He, D. Yuan, "Minimum-Time Link Scheduling for Emptying Wireless Systems: Solution Characterization and Algorithmic Framework", IEEE Trans. On Information Theory, January 2014
9. C. Kam, S. Kompella, A. Ephremides, "Age of Information under Random Updates", IEEE ISIT, July, 2013, Istanbul, Turkey
10. C. Kam, S. Kompella, A. Ephremides, "Effect of Message Transmission Diversity on Status Age", IEEE ISIT, July 2014, Honolulu, Hi (accepted)
11. M. Costa, M. Codreanu, A. Ephremides, "Age of Information with Packet Management", IEEE ISIT, July 2014, Honolulu, HI (accepted)
12. Q. He, V. Angelakis, A. Ephremides, D. Yuan. "Polynomial Complexity Minimum-Time Scheduling in a Class of Wireless Networks", arXiv: 1403.4144 (Submitted to IEEE Trans. On Control and Network Systems)
13. N. Abuzainab, A. Ephremides, "Secure Distributed Information Exchange", IEEE Transactions on Information Theory, April 2014
14. M. Kashef, A. Ephremides, "Energy Efficiency of Transmission Control in Cognitive Radio Networks with CSI", CISS proceedings, Princeton, NJ, March 2014 and submitted to IEEE Transactions on Networking
15. M. Costa, A. Ephremides, "Trade-off of Energy Efficiency versus Performance in Cognitive Wireless Networks", CISS proceedings, Princeton, NJ, March 2014 and also submitted to IEEE Transactions on Networking
16. M. Costa, S. Valentin, A. Ephremides, "On the Age of Channel Information for a Finite-State Markov Model", accepted in IEEE ICC, June 2015
17. M. Costa, M. Codreanu, A. Ephremides, " On the Age of Information in Status Update Systems with Packet Management", submitted IEEE IT transactions.

Interdisciplinarity

My application is interdisciplinary

☐

An interdisciplinary research project is defined in this call for proposals as a project that can not be completed without knowledge, methods, terminology, data and researchers from more than one of the Swedish Research Councils subject areas; Medicine and health, Natural and engineering sciences, Humanities and social sciences and Educational sciences. If your research project is interdisciplinary according to this definition, you indicate and explain this here.

Click here for more information

Scientific report

Scientific report/Account for scientific activities of previous project

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Budget and research resources

Project staff

Describe the staff that will be working in the project and the salary that is applied for in the project budget. Enter the full amount, not in thousands SEK.

Participating researchers that accept an invitation to participate in the application will be displayed automatically under Dedicated time for this project. Note that it will take a few minutes before the information is updated, and that it might be necessary for the project leader to close and reopen the form.

Dedicated time for this project

	Role in the project	Name	Percent of full time
1	Applicant	Anthony Ephremides	20
2	Other personnel with doctoral degree	Vangelis Angelakis	20
3	Other personnel without doctoral degree	PhD Student	80

Salaries including social fees

	Role in the project	Name	Percent of salary	2016	2017	2018	Total
1	Applicant	Anthony Ephremides	10	179,000	184,000	189,000	552,000
2	Other personnel with doctoral degree	Vangelis Angelakis	20	166,000	169,000	173,000	508,000
3	Other personnel without doctoral degree	PhD Student	80	419,000	429,000	439,000	1,287,000
	Total			764,000	782,000	801,000	2,347,000

Other costs

Describe the other project costs for which you apply from the Swedish Research Council. Enter the full amount, not in thousands SEK.

Premises

	Type of premises	2016	2017	2018	Total
1	Local Remuneration	77,000	79,000	81,000	237,000
	Total	77,000	79,000	81,000	237,000

Running Costs

	Running Cost	Description	2016	2017	2018	Total
1	Travel Costs & Publication Costs	Travel Costs & Publication Costs	140,000	170,000	190,000	500,000
	Total		140,000	170,000	190,000	500,000

Depreciation costs

Depreciation cost	Description	2016	2017	2018

Total project cost

Below you can see a summary of the costs in your budget, which are the costs that you apply for from the Swedish Research Council. Indirect costs are entered separately into the table.

Under Other costs you can enter which costs, aside from the ones you apply for from the Swedish Research Council, that the project includes. Add the full amounts, not in thousands of SEK.

The subtotal plus indirect costs are the total per year that you apply for.

Total budget

Specified costs	2016	2017	2018	Total, applied	Other costs	Total cost
Salaries including social fees	764,000	782,000	801,000	2,347,000		2,347,000
Running costs	140,000	170,000	190,000	500,000		500,000
Depreciation costs				0		0
Premises	77,000	79,000	81,000	237,000		237,000
Subtotal	981,000	1,031,000	1,072,000	3,084,000	0	3,084,000
Indirect costs	373,000	391,000	407,000	1,171,000		1,171,000
Total project cost	1,354,000	1,422,000	1,479,000	4,255,000	0	4,255,000

Explanation of the proposed budget

Briefly justify each proposed cost in the stated budget.

Explanation of the proposed budget*

For the implementation of the proposed research activities, the requested funding is intended to partially support the research conducted under the supervision of the primary investigator (PI) prof. Anthony Ephremides. Therefore, the proposal requested budget is targeted to cover: (i) four ITN members, as below, at different percentages of Full Time Equivalent (FTE) involvement, (ii) travel and publication costs associated with the project activities, (iii) the overheads charged by ITN-LiU.

i. Personnel costs:
1. Prof. Anthony Ephremides (PI), is a world-renowned researcher in wireless networking and information theory. Throughout his career he has been accomplishing a wide range of achievements and he is continuously honored with prestigious awards. He presently holds a part time guest professorship at the Mobile Telecommunications (MT) group of ITN-LiU led by Prof. Yuan. The PI will devote 20% of the FTE to the project. The requested budget is 10% of the FTE, since the rest is covered by ITN Faculty resources.

2. Prof. Vangelis Angelakis, (co-PI), is an Assistant Prof. at the MT group, hosting the proposed work. He contributes to the project with his expertise on **optimization and mathematical modeling. The co-PI will also devote 20% of the FTE to the project, coordinating locally the day-to-day research activities.**

3. Newly-hired PhD student. A newly-recruited student will devote 80% of their FTE to the project, handling the day-to-day research activities from proof-of-concept to implementation, development and testing. The requested budget is the total of their 80% of their FTE, since the rest 20% will be covered by ITN teaching budget.
For each of the salaries, the requested budget includes an employer's contribution of 55.14% of the salary. A 2.5% annual increase is also assumed. The applicant holds guest professor contract which is expected to be renewed accordingly upon the successful funding of the current proposal. LiU is an equal-opportunities employer and the new PhD position will be advertised in this spirit.

ii. Travel and publication costs:
The research team shall pursue publishing in top-tier international journals to disseminate the project outcomes. Conferences will also be used to promote the work and get early feedback from the community. Events to consider are top-ranked venues as the IEEE ISIT, IEEE Infocom, IEEE Globecom and the IEEE ICC. To this end travel expenses are requested as below. Furthermore, we foresee a portion of the budget in this category to be used for costs associated with open access publications.

iii. Overheads:
The ITN Department of LiU, where this application is hosted, applies 38% overhead to all cost categories. Personnel costs as topped with a further 64KSEK/FTE for local facilities remuneration.

Other funding

Describe your other project funding for the project period (applied for or granted) aside from that which you apply for from the Swedish Research Council. Write the whole sum, not thousands of SEK.

Other funding for this project

Funder	Applicant/project leader	Type of grant	Reg no or equiv.	2016	2017	2018

CV and publications

CV

<u>Curriculum Vitae:</u> **Anthony Ephremides**

Date of birth: September 19, 1943 Civic Status: Married; U.S citizen

Education

- 1971 PhD, Electrical Engineering, Princeton University, USA.
- 1969 MA, Princeton University, USA.
- 1967 Diploma, National Technical University of Athens, Greece.

Research Achievements of International Reputation

- initiated the field of study of ad hoc wireless networks in the late '70s,
- developed the first distributed algorithm for self-organization of ad hoc networks,
- developed the back-pressure algorithm that is by now established as a seminal characterization of stabilizing the operation of wireless networks,
- introduced the concept of cross-layer design of wireless networks,
- lead the current trend towards energy-efficient network protocol design,
- provided key contributions in the use of network coding in wireless, and numerous others

Academic/Research Positions

- Guest professor, Linköping University (LiU), Department of Science and Technology (ITN), Sweden. 2011 Feb. – today.
- Distinguished University Professor; Cynthia Kim Eminent Professor of Information Technology, University of Maryland (UMD), USA. 2003 August – today.
- Visiting Professor, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland, 1986
- MIT, Laboratory for Information and Decision systems, Visiting Professor, 1985, fall semester.
- University of Maryland, Institute for Systems Research, (ISR, previously known as *Systems Research Center*), 1984 – today, founding member and joint appointment with ECE since 1987.
- Visiting Professor University of California, Berkeley, CA, third quarter of academic year, Department of Electrical Engineering, 1978-1979.
- INRIA (Institut National de Recherche Informatique et Automatique), Rocquencourt, France; (on sabbatical leave 1979).

Publications (summary)

- H-index: 48.
- Published over 130 journal articles, over 300 conference presentations --over 20 since 2014
- Books & book chapters: 23; patents: 6.
- Total citations: over 14500; over 15 publications with 200+ citations; most citations: 1778.

Research Grants & Contracts (selection)

Awarded with **over 80** research grants and contracts, continuously since 1971, from various funding bodies and the industry. A short selection follows:

- U.S. National Science Foundation (**NSF**) grant #147730 Collaborative Research: Energy-Efficient Cognitive Networking. 2011-2013, $173K – Primary Investigator (PI).
- Sweden, **Vetenskapsrådet** grant "Prestandaegenskaper hos trådlösa nätverk", 2012-2013, 1.6 MSEK (PI).
- U.S. NSF research grant on Cooperative Networking Across the Layers. 2009-2012, $371K (PI)
- **Fujitsu** USA Power Control in Cellular Networks, 2006, $50K (PI).
- **NSF Major Research Instrumentation Award**, 2005, $400K (PI)
- **NSF**-ITR Program Vertical Protocol Integration in Wireless Networks, 2002-2005, $1.5M (PI).
- U.S. Office of Naval Research (**ONR**), Network Coding for Sensor Networks, 2005-2007, $300K
- US Army Research Lab Communication Technology Alliance (**CTA**), 2001-2006, $899K/yr (PI)
- **NASA** Center for Hybrid and Satellite Communication Networks 1991-2006 $900K/yr. (co-PI)

- **NSF**, Control and Performance Trade-Offs in Multihop Wireless Networks 1999-2003 $672K (PI)
- Department of Defense (**DoD**) Defense University Research Instrumentation Program, 1997 $300K

Awards & Honors (selection)

Received **over 30 awards**, including **3 best paper awards**. Among the most prestigious are:

- 1984 IEEE Fellow
- 1991 IEEE Donald Fink Paper Award for Best Tutorial Paper published anywhere in the IEEE publications.
- 1996 ACM Sigmobile Award for Outstanding Contributions to Research on Mobility of Systems, Users, Data, and Computers.
- 1999 IEEE Third-Millennium Medal
- 2000 Outstanding Systems Engineering Faculty Award the Institute for Systems Research
- 2002 Best Research Publication Award by the US Naval Research Laboratory
- 2006 Aaron Wyner Distinguished Award for Service and Leadership in Information Theory
- 2012 University of Maryland Distinguished University Professor title
- 2012 Ad Hoc and Sensor Networks (AHSN) Technical Recognition Award

Administrative, Consulting and Industrial Experience (short selection)

- Institutional Council Member of the National Technical University of Athens, 2012
- Evaluation of the ECE Program at the University of Toronto 2005
- Co-founder of Center on Commercial Development of Space (CCDS) on Satellite and Hybrid
- Communication Networks (a 5-year, \$5M, NASA and Industry funded consortium at the University of Maryland), 1991-present, Co-Director 1991-1995
- Invited Panelist for European Union Future Emerging Technologies (FET) Proposal Evaluations (April 2005, April 2006)
- Director of the Fairchild Scholars Program 1980-1985
- President and Founder (1980) of Pontos, Inc., a Maryland technical consulting firm
- Research Consultant of the US Naval Research Laboratory, (Information Technology Division) 1977 –today

Professional Services (short selection)

- Member of the **Board of Governo**rs of the Information Theory, Society of the IEEE
- **President** of the Information Theory Society of the IEEE (1987)
- **IEEE Board of Directors** 1989 and 1990.
- Historian of the IEEE Information Theory Society
- Review Panel for the Evaluation of NASA Research Programs at Goddard Space Center.
- Member and Chair of Technical Program Committee for numerous conferences including IEEE INFOCOM, IEEE ISIT, ACM Mobicom, IEEE WiOpt
- Editorial Board member of numerous journals, including: IEEE Transactions on Automatic Control, IEEE Transactions on Information theory, the Journal of Wireless Networks, and the International Journal of Satellite Communications
- Reviewer of proposals and papers for dozens of agencies, journals, and conferences

Supervision

Supervisor of **over 25 Ph.D.** Dissertations, including:

- Ramesh Rao (1984), h-index: 48, Professor, ECE University of California, San Diego; Director, UCSD Calit2, USA.
- Leandros Tassiulas (1991), h-index: 53, Computer Engineering and Telecommunications Dept.University of Thessaly, Volos Greece.
- Eytan Modiano (1992): h-index: 44, Interim Associate Department Head, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, USA.

Curiculum Vitae
Vangelis Angelakis

Education

July 2008:	Ph.D. Department of Computer Science, University of Crete, Greece.
March 2004:	M.Sc. (Telecommunications & Networks) Dept. of Computer Science, University of Crete, Greece.
July 2001:	B.Sc. Degree of the Dept. of Computer Science, University of Crete, Greece.

Research Experience

Oct. 2013 – Present	Assistant professor (*Junior Universitetslektor*), at the Department of Science & Technology (*ITN*), Linköping University (*LiU*), Sweden.
Aug. 2014 – Present	Visiting scholar, MAPCI - Mobile and Pervasive Computing Institute at EIT, Lund University.
Jul. 2014 – Dec. 2014	Guest researcher, Converge ICT Solutions & Services, Greece (*on "overseas contract" with LiU*).
May 2013 – Nov. 2013	Guest researcher, Department of Electronics and Information Engineering, Huazhong University of Science and Technology (HUST), China (*on "overseas contract" with LiU*).
Oct. 2009 – Sep. 2013	Postdoctoral researcher (EU-FP7 Marie Curie IAPP Fellow 2009-'11) at LiU-ITN.
Jan. 2012 – Mar. 2012	Senior research fellow, RANPLAN Wireless Network Design Ltd., UK (*on leave from LiU*).
Jul. 2008 – Sep. 2009	Postdoctoral researcher at the Telecommunications & Networks Laboratory (*TNL*) in the Institute of Computer Science (*ICS*) of the Foundation for Research and Technology –Hellas (*FORTH*).
Nov. 2005 – July 2008	Graduate research assistant at FORTH-ICS.
Jun. – Oct. 2005:	Visiting research associate at the Institute for Systems Research (*ISR*), Clark School of Engineering, University of Maryland - College Park, USA.
Sep. 2001 – May. 2005	Graduate research assistant at FORTH-ICS.

Research Grants

Mar. 2015 (awarded)	Scientist in Charge: "**WiVi-2020**" EU-H2020 MSCA-ITN. Starts 2015: Q4. Duration 4 years. Budget (@LiU) **4.8 Mkr**.
Sep. 2014 (awarded)	Work Package Leader: "ACT5G" EU-H2020 MSCA-ITN. Starts 2015: Q2. Duration 4 years.
Sep. 2014 (awarded)	Fellow: "DECADE" EU-H2020 MSCA-RISE. Duration 4 years.
May 2014 – Present	Fellow: "Framtidens mobilitet" Norrköpings fond för Forskning och Utveckling. Duration 4 years.
Jan. 2014 – Present	Project Cordinator (Project Manager in Year 1): **"SOrBet"** EU-FP7 MC-IAPP-2013. Budget (@LiU) **4.7Mkr**. Duration 4 years.
Sep. 2013 – Present	Scientist in Charge: **"RERUM"** EU-FP7 SMARTCITIES-2013. Duration 3 years. Budget (@LiU) **3Mkr**.
Mar. 2013 – Present	Project Manager: **"**MESH-WISE**"** EU-FP7 MC-IAPP-2012. Duration 4 years.
Jun. 2013 – Present	Fellow: **"**DETERMINE**"** EU-FP7 MC-IRSES-2012. Duration 4 years.
Oct. 2012 – Present	Fellow: **"**WINDOW**"** EU-FP7 MC-IRSES-2012. Duration 4 years.
Nov. 2011 – Oct. 2014	Fellow: "Performance Characteristics of Wireless Networks" Vetenskapsrådet 2011**.** Duration 2 years (extended to 3).
Oct. 2011 – Dec 2011	Fellow: "Fundamental Capacity Analysis in Wireless Communication Systems" ELLIIT Personal Career Grant. Duration 2 months.
Jan. 2008 – Sep. 2009	Fellow: "EU-MESH"EU-FP7 ICT. Duration 2.5 years.
May 2005 – Apr 2008	Fellow: "Wireless Ad hoc Networks: *Researching methods for security, routing, trust management and position locationining*" Greek Secretatiat of Science and Technology - ΠΕΝΕΔ-2003 (Program for the Support of Research Dynamic). Duration 4 years.

Publication summary

One Book (editor), Three Book Chapters, 8 Journal papers, 28 papers and 15 demos/posters in international, indexed, peer reviewed conferences.
Citations: **195** (172 since 2010); h-index: **8**; [Source: Google Scholar, Mar. 2014]

Supervision Experience

PhD Co-Supervision:

Oct. 2014 – present **Ioannis Avgouleas**, Performance analysis of cooperative wireless networks, (Licenciate: ca. **2017** Q2).

Sep. 2011 – present **Qing He,** Revisiting optimal link activation and minimum-time scheduling in wireless networks, (Licenciate Nov. **2014**).

Sep. 2011 – present **Lei Lei,** Radio Resource optimization for OFDM-based broadband cellular systems (Licenciate Apr. **2014**).

Student Supervision:

Supervisor for ten completed BSc/MSc theses, at both LiU and UoC.

Professional Services

- **Committee member** for the defense of PhD Thesis: "Improving Network Performance Through Multipath Utilization for Wireless Mesh Networks," by Manolis Ploumidis, CSD-UoC (Mar. 2015).
- **Co-Chair** IEEE Globecom 2015 full day workshop "Optimizing Heterogeneous Networking Technologies for the Internet of Things" (Feb. 2015).
- **Evaluator** for the Qatar National Research Fund (Feb. 2015).
- **Demo & Poster chair** in IEEE CAMAD 2015 (Oct. 2014).
- **Tutorials chair** in IEEE CAMAD 2014 (May 2014).
- **Organization committee** member for the 2014 SNOW workshop in Åre, Sweden (Apr. 2014).
- **Special Session organizer & chair** for "RESONANT" in IEEE CAMAD 2014 (Mar. 2014).
- **Associate Editor**: Journal of Communications and Networks (JCN) (May 2013 - present).
- **Special Session organizer & chair** for "RESONANT" in IEEE CAMAD 2013 (May 2013).
- **Evaluator** of the Greek Secretariat for Research and Technology (GSRT) for the "ΑΡΙΣΤΕΙΑ II" (Excellence II) action (Feb. 2013).
- **Steering committee** member for the 2013 SNOW workshop in Finland (Apr. 2013).
- **Editorial advisory board** member for: "Mobile Computing over Cloud: Technologies, Services, and Applications", IGI International 2013 (Dec. 2012).
- **Award evaluator** for the 2009-2011 IEEE VTS & AESS Joint Greece Chapter Thesis Award in Advanced Systems in Wireless and Mobile Communications (Nov. 2012).
- **Special session organizer & chair** of the IEEE CAMAD 2012 Resource Management Optimization for "Heterogeneous Next Generation Wireless Access Networks". (Oct. 2012).
- **Swedish Substitute Member** for the Management Committee of COST Action IC1101 "Optical Wireless Communications - An Emerging Technology". (Oct. 2011 - present).
- **Local Arrangement Chair** for the 2011 SNOW workshop in Sälen, Sweden. (Mar. 2011).
- **TPC** Member, Reviewer & Session chairing voluntary duties for numerous Journals & Conferences throughout the last ten years, amongst which:
  - IEEE PerCom 2005, 2014
  - Elsevier COMCOM
  - Elsevier COMNET
  - Elsevier Ad Hoc Networks
  - IEEE WoWMoM 2008-'13
  - IET Communications
  - IEEE HotMESH 2009-'12
  - Future Network & Mobile summit 2009-'11
  - FTRA FutureTech 2010
  - ICST Mobilight 2009, 2010
  - IEEE/ACM Transactions on Networking
  - IEEE Transactions on Parallel and Distributed Systems
  - IEEE Communications Magazine
  - IEEE Communication Letters
  - IEEE ICC 2009-'14
  - IEEE Globecom 2011-'14
  - IEEE SaCoNet 2012-'14
  - IEEE WCNC 2012
  - IEEE ICCCN 2013
  - IEEE VTC 2007- '15

  …and many more.

Publication list

A. Ephremides' summary of publications

Citation numbers are given for publication statistics from Google Scholar as of Apr. 2014.

A. Five most cited publications:

1. "Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks," (with L. Tassiulas), in IEEE Transactions on Automatic Control, 37:12, Dec 1992.

Number of citations: 1985

2. "On the construction of energy-efficient broadcast and multicast trees in wireless networks," (with J. Wieselthier and G.D. Nguyen), in Proc. IEEE INFOCOM 2000. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies. March 2000.

Number of citations: 1208

3. "The Architectural Organization of a Mobile Radio Network via a Distributed Algorithm," (with Baker, D.), in IEEE Transactions on Communications, v.29 nr.11, Nov 1981.

Number of citations: 893

4. "A design concept for reliable mobile radio networks with frequency hopping signaling," (with J.Wieselthier and D. Baker), in Proceedings of the IEEE, v.75 nr.1, Jun. 1987.

Number of citations: 841

5. " Joint scheduling and power control for wireless ad hoc networks," (with T. ElBatt), in IEEE Trans. On Wireless Communications, vol.3, no.1, Jan. 2004.

Number of citations: 829

B. Publications' list

B1. International Journal Papers

1. G.D. Nguyen, S. Kompella, J.E. Wieselthier, A. Ephremides, "Simultaneous Schedule-Based Transmission by Primary and Secondary Users for Heavy-Traffic Cognitive Radio Networks," IEEE Transactions on Vehicular Technology, 64(3), 2015
2. N. Pappas, M. Kountouris, A. Ephremides, A. Traganitis, "Relay-assisted Multiple Access with Full-duplex Multi-Packet Reception," in IEEE Transactions on Wireless Communications, 99, 2015.
3. J. Jeon, A. Ephremides, "On the Stability of Random Multiple Access With Stochastic Energy Harvesting," IEEE Journal on Selected Areas in Communications, 33(3), 2015
4. C. Kam, S. Kompella, G. D. Nguyen, A. Ephremides, J. Zaihan "Frequency Selection and Relay Placement for Energy Efficiency in Underwater Acoustic Networks," IEEE Journal of Oceanic Engineering, 39(2), 2014.
5. V. Angelakis, A. Ephremides, Q. He, D.Yuan "Minimum-Time Link Scheduling for Emptying Wireless Systems: Solution Characterization and Algorithmic Framework," IEEE Transactions on Information Theory, 60(2), 2014. **– number of citations1**
6. A. Fanous, Y. E. Sagduyu, A. Ephremides, "Reliable Spectrum Sensing and Opportunistic Access in Network-Coded Communications", IEEE Journal on Selected Areas in Communications, 32(3), 2014. **– number of citations5**
7. J. Jeongho M. Codreanu, M. Latva-aho, A. Ephremides, "The Stability Property of Cognitive Radio Systems with Imperfect Sensing," IEEE Journal on Selected Areas in Communications, 32(3), 2014. **– number of citations4**
8. S. Kompella, G.D. Nguyen, C. Kam, J. E. Wieselthier, A. Ephremides, "Cooperation in Cognitive Underlay Networks: Stable Throughput Tradeoffs," IEEE/ACM Transactions on Networking, 22(6), 2014.
9. C. Kam, S. Kompella, G. D. Nguyen, J. E. Wieselthier, A. Ephremides, "Cognitive Cooperative Random Access for Multicast: Stability and Throughput Analysis," IEEE Transactions on Control of Network Systems, 1(2), 2014 **– number of citations4**
10. N. Pappas, A. Ephremides, A. Traganitis, "Stability and performance issues of a relay assisted multiple

access scheme with MPR capabilities," Computer Communications, 42, 2014. **– number of citations:** 9

11. N. Abuzainab, A. Ephremides, "Secure Distributed Information Exchange," IEEE Transactions on Information Theory, 60(2), 2014
12. M. Kashef, A. Ephremides, "Optimal Partial Relaying for Energy-Harvesting Wireless Networks," IEEE/ACM Transactions on Networking, 2014
13. A. Fanous, A. Ephremides, "Access Schemes for Mitigating the Effects of Sensing Errors in Cognitive Wireless Networks," IEEE Transactions on Wireless Communications, 13(6) 2014 **– number of citations3**
14. A. Fanous, A. Ephremides, "Stable Throughput in a Cognitive Wireless Network," IEEE JSAC, 31(3), 2013. **– number of citations14**
15. P. C. Weeradana, M. Codreanu, M. Latva-aho, A. Ephremides "Multicell MISO Downlink Weighted Sum-Rate Maximization: A Distributed Approach," IEEE Transactions on Signal Processing, 61(3),2013. **– number of citations14**
16. G. D. Nguyen, J. E. Wieselthier, and A. Ephremides. "Communication-theoretic analysis of capture-based networks". Journal of Communications and Networks 14:3 (2012) pp. 243-251.
17. N. Abuzainab, and A. Ephremides. "Energy Efficiency of Cooperative Relaying over a Wireless Link", IEEE Transactions of Wireless Communications 11:6 (2012) pp. 2076-2083. **– number of citations:** 10
18. G. Nguyen, S. Kompella, J. Wieselthier and A. Ephremides "Schedule-based Transmissions for Heavy-Traffic Cognitive Radio Networks", IEEE Transactions on Wireless Communications (*accepted* 2012).
19. M. Kashef and A. Ephremides "Optimal packet Scheduling for Energy harvesting Sources on Time Varying Wireless Channels", Journal of Communications and Networks, 14:2, (2012) pp 121-129. **– number of citations:** 20
20. B. Rong and A. Ephremides. "Cooperative Access in Wireless Networks: Stable Throughput and Delay Issues", IEEE Trans on Information Theory" In: Information Theory, IEEE Transactions on 58.9 (2012), pp. 5890–5907. **– number of citations:** 14
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CV

Name: Anthony Ephremides	**Doctorial degree:** 1971-09-30
Birthdate: 19430919	**Academic title:** Professor
Gender: Male	**Employer:** Linköpings universitet

Research education

Dissertation title (swe)
NA

Dissertation title (en)
Multiplicity of Random Processes and its Application

Organisation	Unit	Supervisor
Princeton University, USA Not Sweden - Higher Education institutes		John Thomas

Subject doctors degree	ISSN/ISBN-number	Date doctoral exam
20204. Telekommunikation		1971-09-30

CV

Name: Vangelis Angelakis	**Doctorial degree:** 2008-07-10
Birthdate: 19771007	**Academic title:** Doktor
Gender: Male	**Employer:** Linköpings universitet

Research education

Dissertation title (swe)		
Power Control Design Considerations in Ad Hoc and Mesh Networking		
Dissertation title (en)		
Power Control Design Considerations in Ad Hoc and Mesh Networking		
Organisation	**Unit**	**Supervisor**
University of Crete, Greec Not Sweden - Higher Education institutes	Department of Computer Science	Apostolos Traganitis
Subject doctors degree	**ISSN/ISBN-number**	**Date doctoral exam**
20204. Telekommunikation		2008-07-10

Publications

Name: Anthony Ephremides	**Doctorial degree:** 1971-09-30
Birthdate: 19430919	**Academic title:** Professor
Gender: Male	**Employer:** Linköpings universitet

Ephremides, Anthony has not added any publications to the application.

Publications

Name: Vangelis Angelakis	**Doctorial degree:** 2008-07-10
Birthdate: 19771007	**Academic title:** Doktor
Gender: Male	**Employer:** Linköpings universitet

Angelakis, Vangelis has not added any publications to the application.

Register

Terms and conditions

The application must be signed by the applicant as well as the authorised representative of the administrating organisation. The representative is normally the department head of the institution where the research is to be conducted, but may in some instances be e.g. the vice-chancellor. This is specified in the call for proposals.

The signature*from the applicant*confirms that:

- the information in the application is correct and according to the instructions form the Swedish Research Council
- any additional professional activities or commercial ties have been reported to the administrating organisation, and that no conflicts have arisen that would conflict with good research practice
- that the necessary permits and approvals are in place at the start of the project e.g. regarding ethical review.

The signature *from the administrating organisation* confirms that:

- the research, employment and equipment indicated will be accommodated in the institution during the time, and to the extent, described in the application
- the institution approves the cost-estimate in the application
- the research is conducted according to Swedish legislation.

The above-mentioned points must have been discussed between the parties before the representative of the administrating organisation approves and signs the application.

Project out lines are not signed by the administrating organisation. The administrating organisation only sign the application if the project outline is accepted for step two.

Applications with an organisation as applicant is automatically signed when the application is registered.