Towards New Routing Solutions for Wireless Industrial Networks

Neda Petreska
Fraunhofer Institute for Communication Systems ESK
Munich, Germany, neda.petreska@esk.fraunhofer.de

***Abstract*—Routing in wireless multi-hop networks has been addressed by numerous research works so far. However, the increased usage of Machine-to-Machine (M2M) and industrial communication has set even higher goals regarding Quality-of-Service (QoS) and energy consumption. There are hardly works which combine both reliable and in time packet delivery as well as energy-efficiency. In this PhD thesis we are interested in energy-efficient routing solutions under QoS constraints such as Bit-Error-Rates (smaller than 10^{-5}) and delays not bigger than several milliseconds. By means of stochastic network calculus and Gilbert-Elliott (GE) model, physical channel characteristics will be embedded in the performance definition of network routes to enable additional energy management.**

I. Motivation

During the last years we have witnessed a constantly increasing employment of wireless networks in industrial automation. However, there is still a huge potential for wireless real-time applications in the field of M2M communication with strict QoS requirements. Unfortunately, wireless links still fail to provide a reliable and secure connection as well as guaranteed and in time packet delivery. In order to define service guarantee bounds of wireless channels, a precise and thorough network analysis is needed in the system design phase. The theory of stochastic network calculus provides a solid mathematical framework for estimation on resource availability and QoS performance of wireless networks.

Considering the limitations of industrial automation and M2M communication, the problem of finding the optimal path, which meets time, outage and energy limitations at the same time, has not been solved so far. Many works analyze either QoS-aware or energy-efficient routing in wireless networks, but very rarely both aspects together. The few doing this are only considering the deadline, but not the end-to-end outage probability as a QoS constraint [1], [2]. Moreover, to the best of my knowledge, there is no attempt to address energy-efficient routing while doing physical parameter channel modeling on one side and QoS performance guarantee evaluation and traffic engineering on the other. This PhD thesis focuses on determining the optimal route in a multi-hop wireless network with respect to both end-to-end delay and outage constraints as well as minimum energy consumption. Due to the early phase of the thesis, the theoretical approach towards construction of such routing algorithm will be outlined while evaluation results are considered in future work.

II. System Model

A static multi-hop wireless network with several simultaneous data flows is considered. Each data flow is characterized with an end-to-end deadline T as well as Bit-Error-Rate (BER). We observe a data flow from source Src via several other nodes to a destination Dst. The time amount needed to forward the packet between two neighbouring nodes along the path is t_i. Each link has a bandwidth B. Using the theory of network calculus for servers in series, performance bounds of the flow for a specific route in the network will be computed. According to the theory, the behaviour of a node, link or channel in a wireless network is defined by its service curve. In the underlying system, each link is modeled by the GE model [3] and afterwards, the service curve of the channel is derived. Having this, a min-plus convolution of all service curves along a path results into an end-to-end service curve and determination of delay and backlog bounds. This information together with the total transmit power along the route results into an optimal route definition.

A. Stochastic Network Calculus

As wireless links can only provide stochastic service guarantees, the theory of deterministic network calculus is not sufficient to describe their behaviour. This motivated an extension of the theory into its stochastic variant [4]. According to stochastic network calculus, an arriving process into the system is described by the $(\sigma(\theta), \eta(\theta))$-traffic characterization for $\theta > 0$. Thereby, $\sigma(\theta)$ is the burstiness parameter and $\eta(\theta)$ is the upper bound on the traffic flow average rate. Furthermore, an incoming flow $A(\tau, t) = A(t) - A(\tau)$ denotes the cumulative number of bits arriving in the time interval $(\tau, t]$ [4]. Similarly, the cumulative departure of the system is denoted by $D(t)$. As described in [3], the service guarantee of a system, e.g., a communication link, a channel, a multi-hop path or a whole network, is expressed by a statistical service curve $S(t)$. This curve provides a lower bound on the departures, which can be violated with some probability. We say, the system has a service curve $S(t)$ with deficit profile $\varepsilon_S(\sigma_S) \in [0, 1]$ and parameter $\sigma_S \geq 0$, if $\forall t \geq 0$ it holds $P[D(t) < A \otimes S(t) - \sigma_S] \leq \varepsilon_S(\sigma_S)$, where $\otimes$ represents the min-plus convolution [4]. The deficit profile defines the probability that a server lacks to provide the incoming flow with its demanded service.

From the other side, statistical envelopes (usually also referred to as statistical arrival curves) provide upper bounds on arrival processes in a system. Arrival process with an envelope $E(t)$ with overflow profile $\varepsilon_E(\sigma_E) \in [0,1]$ and $\sigma_E \geq 0$ is defined as $P[A(t) > A \otimes E(t) + \sigma_E] \leq \varepsilon_E(\sigma_E), \forall t \geq 0$. By means of moment generating function (MGF), the min-plus (de)convolution is transformed into corresponding operators $\star$ and $\circ$ in conventional algebra[1], which simplifies the computation. We define the MGF of an arrival process as $\mathrm{M}_A(\theta, t) = \mathbb{E}[e^{\theta A(t)}]$, where θ is a free parameter [3].

B. Gilbert-Elliott Channel Model

When working with strict time and outage limitations for industrial wireless applications, it is very important to address the conditions under which the communication link will be in outage, i.e. will fail to meet the QoS requirements. We then talk about an impairment process and strict stochastic service curve. According to [4], the wireless channel can be modeled as a strict stochastic server with two states: "good" and "bad". If due to some impairment, the channel is in a "bad" state, no data can be received correctly. Moreover, in a multi-flow channel, if the server is shared between several incoming flows, the impairment within the server can happen due to mutual disturbance between the flows. In this case, the impairment process is represented by the interference between different data flows. We therefore divide the stochastic service process $S(t)$ into an ideal service process $\hat{S}(t)$ and an impairment process $I(t)$: $S(t) = \hat{S}(t) - I(t)$.

In order to define the service a channel provides to an incoming flow, we will further characterize the arrival of the impairment process. In order to achieve this, we model the channel according to the GE model. If at time t_i the channel is in a state X_i, then we define the transit state probabilities as $p = P(X_{i+1} = B|X_i = G)$ and $q = P(X_{i+1} = G|X_i = B)$.

The MGF of a random process S modeled according to GE is defined by $M_S(\theta, t) = \mathbf{P}e^{(Q-\theta H)t}\mathbf{1}$, with $H = diag(h, 0)$. h represents the processing rate of the channel (or the number of correctly received packets during a time unit) in the good state [5]. Q is the transition probability matrix with elements $q_{11} = -p$, $q_{12} = p$, $q_{21} = q$ and $q_{22} = -q$ and the stationary state probability row vector $\mathbf{P} = \left(\frac{q}{p+q}, \quad \frac{p}{p+q}\right)$. Knowing this, for the MGF of process S for $\forall t \geq 0$ and all θ it holds $M_S(\theta, t) \leq e^{-\theta\rho_S(-\theta)t}$ [5], where

$$\rho_s(\theta) = \frac{1}{2\theta}(h\theta - p - q + \sqrt{(h\theta - p + q)^2 + 4pq}). \tag{1}$$

For the impairment process it holds $M_I(\theta, t) \leq e^{\theta\rho(\theta)t}$. Here $\rho(\theta)$ follows (1) with the difference, that p and q are switched: A "bad" state for the channel is a "good" state for the impairment process, as in that state it consumes the whole channel bandwidth, while in the "good" state for the channel, the impairment process does not consume any service.

Considering a work-conserving channel with peak rate h and following the definition for the stochastic service process $S(t)$, according to [5] we define

[1] $X \star Y(t) = \sum_{s=0}^{t} X(s)Y(t-s)$; $X \circ Y(\tau, t) = \sum_{s=0}^{\tau} X(s+t)Y(s)$

$$\begin{aligned} M_{S(t)}(\theta) &= M_{ht-I(t)}(\theta) = M_{ht}(\theta)M_{I(t)}(\theta) \\ &\leq e^{-\theta ht + \frac{t}{2}(h\theta - q - p + \sqrt{(h\theta-q+p)^2+4pq})} \\ &= e^{\frac{t}{2}(-h\theta - q - p + \sqrt{(h\theta-q+p)^2+4pq})}. \end{aligned} \tag{2}$$

Eq. (2) defines the bound on the MGF of a service process with impairment for a single link. By doing the end-to-end link concatenation (i.e. min-plus convolution) we will derive the performance bounds of the whole path. For the MGF of the service process for a path consisting of n links, each having a strict service envelope process $S_i(t), i = 1, .., n$, it holds:

$$\begin{aligned} M_{S(t)}(-\theta) &= M_{S_1(t)\otimes ... \otimes S_n(t)} \\ &\leq [M_{S_1(t)}(-\theta) \star ... \star M_{S_n(t)}(-\theta)](t). \end{aligned} \tag{3}$$

Finally, if $S(t)$ is the end-to-end strict service envelope process and $A(t)$ is the incoming flow, then the probability that the delay of the path exceeds the QoS parameter T, is bounded by $P\{D(t) > T\} \leq [M_S(-\theta) \circ M_A(-\theta)](t, T)$.

III. Future Work

In order to compute the energy consumption of a path satisfying certain QoS requirements, the needed transmission power per link will be included in the computation. As the transmission power depends on the channel gain h^2

$$P_{tx} = \frac{P_{noise}}{h^2 ln(BER)}(1 - 2^{\frac{\eta(\theta)}{B}}), \tag{4}$$

mapping the channel parameters into the GE model will add the energy-efficiency aspect into the theoretical model. The end-to-end cost C of the path between Src and Dst is a function of the end-to-end service curve, which in turn depends on the transmit power, i.e. $C = f(M_{S(t)}(-\theta, P_{tx})$. The routing algorithm will be centrally executed and will determine the optimal routes between every pair of nodes in the network. Multiple suitable paths can be selected to ensure redundancy in case of node failure.

The concepts explained so far present first theoretical insights towards optimal route selection in a wireless industrial multi-hop network under strict QoS requirements. Performance validation will be one major further step, when the resulting routing algorithm will be compared to existing ones by means of simulation and real test-bed experiments.

References

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