2014 IEEE 33rd International Symposium on Reliable Distributed Systems

Dependable Admission Control for Mission-Critical Mobile Applications in Wireless Mesh Networks

Timo Lindhorst, Burkhard Weseloh, Edgar Nett
University of Magdeburg
Institute for Distributed Systems
Universitätsplatz 2, 39106 Magdeburg, Germany
{lindhors,weseloh,nett}@ovgu.de

***Abstract*—Wireless Mesh Networks (WMNs) provide a promising foundation for a flexible and reliable communication infrastructure in industrial environments. Meeting the QoS demands of industrial applications, though, requires the deployment of an admission control to avoid network overload. The presence of mobile stations, however, causes dynamics within the network that severely impacts the available capacity. For instance, if a communication route switches from one to two hops, twice the resources are consumed due to self-interference. To neither jeopardize QoS guarantees nor having to cancel present flows, our dependable admission control scheme foresees and considers those dynamics during resource reservation to handle station mobility. We describe a highly dependable approach and further propose an estimation method that improves network efficiency. The evaluation results show that our novel approach allows for a dependable admission control even in presence of mobile stations and thus enables the network to provide a new class of guarantee for mission-critical mobile applications.**

I. Introduction

The current and expected evolution in factory automation imposes increasing requirements on the deployment of suitable communication systems. Cyber-physical production systems [9] trigger a paradigm shift from centrally controlled manufacturing systems towards decentralized systems of cooperative, networked components. Intelligent manufacturing systems, storage systems, and transport systems operate autonomously and exchange relevant information to ensure a flexible, highly adaptive, and self-optimizing production process.

The envisioned flexibility and the integration of mobile components require the deployment of a wireless communication system that allows for ad-hoc communication and adapts to the actual environmental conditions and present demands of the industrial applications. Furthermore, production processes require a highly dependable communication service that provides QoS-guarantees.

Wireless Mesh Networks (WMNs) [1], [2] are a suitable foundation to provide a flexible communication service. Instead of a wired backbone well known from common WLAN infrastructure networks, mesh routers span a fully wireless network, which provides self-configuration and self-healing capabilities by using a multi-hop routing protocol.

To provide the dependability required by industrial applications, however, we need additional mechanisms to enhance the basic routing protocol. A major aspect to ensure good performance and provide QoS guarantees is to avoid network overload, which would cause high latencies and packet losses. This can be achieved by an appropriate admission control scheme. This, however, requires a precise assessment of the network utilization induced by application's communications.

A correct assessment of available network resources as well as the assessment of the resources required for a certain communication is already challenging in static wireless networks. Links with different physical bit rates (caused by different modulation techniques) require different amount of network resources to transmit the same amount of data. As the medium is shared, transmissions suffer from both external and self-interference. The latter is especially challenging in multi-hop wireless networks, as successive links on a route interfere in general and thus share the available capacity.

Mobile applications, i. e. applications running on mobile stations in the network, further exacerbate the problem of a correct resource assessment, as the mobility causes dynamics regarding the required resources for transmissions to mobile stations. Thus, even though there might be enough resources to admit a new communication at the time it is requested, the movement of a station might cause increasing resource requirements that would eventually cause network overload. The reason for the varying resource requirements is twofold: First, the physical bit rate on a distinct link between two stations changes according to the present distance and environmental conditions. Second, if the route between sender and receiver changes, the required resources may increase due to self-interference caused by additional hops.

In industrial environments there are also mission-critical applications, i. e. applications, that expect an admitted communication to last for the entire runtime of the application. The previously explained variation of the resources required for a distinct communication, however, poses a challenge to admission control for mission-critical applications: If an increase of resource consumption caused by mobile

1060-9857/14 $31.00 © 2014 IEEE
DOI 10.1109/SRDS.2014.39

applications leads to network overload, we cannot revoke previous admissions to prevent this.

To provide a dependable admission control that must not revoke admissions for mission-critical applications, the resource assessment and the admission management have to consider the dynamics caused by mobile stations. It is not sufficient to only consider the present situation when QoS communications are initially requested. Instead, it is important to ensure that the provided guarantees can also be maintained when mobile stations move within the operational area causing the network to change.

Static planning of mobility and communication characteristics contradicts the flexibility requirement of the envisioned application scenario of widely autonomously acting industrial components. The fundamental challenge is the existence of two autonomous but interdependent systems, i. e. the industrial application and the self-optimizing network. On the one hand, the applications rely on the communication network. On the other hand, the service provided by the network depends on the present state of the application, e. g. the load induced by existing and requested communications and the mobility of stations. Hence, the network has to provide service guarantees without being able to control the conditions.

In our solutions approach, the network considers mobility patterns and application behavior from observations in the past. Admission control should use predictive models to provide QoS also for dynamic mobile application. The objective of this paper is to outline mechanisms to explicitly consider dynamics in a way that allows to predict the varying resource requirements for communicating mobile stations in a limited-scale industrial wireless mesh network. We will implement and evaluate two mechanisms that estimate the maximum resource requirements to provide a dependable admission control scheme for mobile applications. This enables the network to provide a new class of guarantees for mission-critical mobile applications.

The rest of the paper is structured as follows: In section II we discuss related work. Section III describes our basic admission control scheme, while section IV extends the approach to explicitly handle station mobility. We elaborate on predictive admission control and present two approaches to estimate an upper bound for the utilization to be expected from communications involving mobile stations. In section V we evaluate our approach regarding the objective of a dependable admission for mission-critical mobile applications. Furthermore, we analyse the efficiency of the proposed mechanisms and the overall network utilization. Finally, we conclude our work in section VI.

II. Related Work

In a wireless communication network, the main resource to be managed is the utilization of the wireless medium. As it is shared among neighboured stations, transmissions of different nodes add up to the present utilization. If the utilization exceeds a certain level, packet losses and increased latencies occur due to overload [8]. Hence, a precise assessment of the present utilization is crucial to provide QoS guarantees.

In [5], a utilization model is presented for hybrid wired-wireless networks, which however only addresses communication in one cell and does not cope with wireless multi-hop communication. Furthermore, the physical bit rate is fixed and thus does not allow optimal performance.

Wu et al. present SoftMAC [14], an approach that integrates physical rate control as well as admission control to support multimedia services over wireless multi-hop networks. However, they do not consider mobile nodes.

In [12] the authors propose an improvement to AODV to provide QoS in WMNs. They use a measurement-based approach to determine the present load in the network. By using a load-based routing metric, the performance of the network is improved in terms of higher throughput and lower latencies. However, no real guarantees can be provided.

In [3], an approach for bandwidth guaranteed routing in multi-radio WMNs is presented. The authors use given link capacities to design an AODV-based routing, which only establishes routes if the requested bandwidth can be guaranteed. The evaluation shows that the approach outperforms other approaches in terms of admission rate. However, the authors do not describe how to determine the link capacities and it is not presented whether the guarantees could really be kept.

In [15] an admission control for multipath routing is presented. The authors describe a sophisticated analytical model to estimate the available bandwidth based on properties like the physical bit rate, error rates, and back-off times utilizing parameters for the present contention window size. However, when determining the bandwidth requirement for new communications, they consider the same fixed values for all links in the network, e. g. a constant physical bit-rate of 2 MBit/s. They also only consider a static network when deciding about the acceptance of new communications and do not account for node mobility.

Hou et al. propose a routing scheme with bandwidth guarantees in [7]. They use information about available capacity on links and a clique-conflict-graph to model the impact of interfering transmissions to find the path that allows the highest possible throughput. However, neither the concept nor the evaluation considers the effect of mobility within the network.

In [13] we present an approach to model and assess the medium utilization based on cross-layer monitoring to deploy an admission control that timely adapts to varying conditions and dynamics. However, in case of station mobility, network overload may only be avoided by canceling previously admitted data flows. Thus, the approach is not able to provide dependable QoS guarantees in presence of

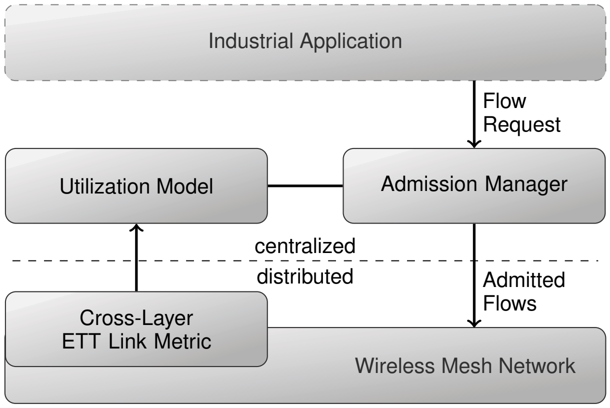

Figure 1: Feedback Loop for Admission Control

mobile stations in the network, as admissions may always be revoked when resource requirements increase due to network variation.

III. Admission Control in Industrial WMN

In this section we describe our basic admission control scheme for industrial WMNs, which is adopted from [13] and depicted in figure 1. It consists of a control loop that continuously assesses the current medium utilization using a cross-layer ETT (Expected Transmit Time) metric. A central admission manager decides on applications' request to communicate, whether further transmissions can be permitted without provoking medium overload and thus a degradation of the QoS in terms of increased latencies and packet losses. The overall architecture as well as evaluations for both the ETT metric and the utilization model can be found in [13] – the main components are outlined for comprehension in the following.

A. Routing

Our WMN is based on a link-state routing protocol [4], which provides self-optimization and -healing capabilities and thus adapts to dynamic conditions or environmental changes. We prefer link-state routing over on-demand routing as we consider the envisioned industrial environment as limited in both size and dynamics. The proactive determination of the entire network topology allows for instantaneously available routes and quality information.

B. Cross-layer ETT Link Metric

For an accurate and timely assessment of link qualities, we designed and implemented a cross-layer ETT metric. Based on information and statistics of the physical and MAC layer, e. g. the presently used physical bit rate and the average number of MAC layer retransmissions, the time required to transmit a data frame is determined for each link. Changing conditions, like adjustment of physical bit rates or varying error rates due to increased distance to a mobile station, are timely considered by cross-layer monitoring. Using the ETT as link metric allows to minimize the network load induced by communication.

C. Utilization Model

The cross-layer ETT metric not only minimizes the induced network load, it also allows for a timely and accurate determination of the present utilization of the network as well as the utilization induced by a new communication: Based on individual link costs c_i, a packet's end-to-end transmission time can be obtained by $C = \sum c_i$. The utilization U_f for a communication f with the given packet rate R_f is approached as $U_f = R_f \cdot C_f$. As we model the overall capacity of the network as one global resource that is shared by all transmissions in the network, the overall utilization is obtained as $U = \sum U_f$. This is a pessimistic simplification as sufficiently distant stations can transmit simultaneously. However, in the envisioned limited-scale industrial networks, this may only result in a low overestimation of the present and induced load. While this may sacrifice some efficiency, it is uncritical regarding our objective of a dependable admission control scheme.

D. Central Admission Manager

The objective of the central admission manager (CAM) is to prevent network overload, as overload severely degrades QoS properties of the communication: Congestion results in growing queuing delays and packet losses. Communications are only permitted if admitted by the CAM, which determines the present and expected medium utilization by means of the upper described utilization model. Hereby, certain resource reserves are kept to be tolerant against faults and allow local recovery mechanisms in the network without taking risk of temporary medium overload ($U \leq U_{max} < 1$). Further details can be found in [13].

E. Flows – the Application Interface

To define relevant attributes of a communication, the notion of *flows* is introduced. Before performing any communication, the application needs to request a flow, specifying its requirements as follows:

- *source* and *destination*, the nodes which send and receive the data, respectively.
- the network *load* created by the flow's sender, specified as the message size [bytes] and message rate [1/s].
- the *priority* (importance) of the flow, compared to other flows on the network. This needs to be decided at design time.

Communication may start as soon as the flow is admitted by the CAM. The application can further register a handler for receiving termination notifications. This allows to terminate best effort flows and flows of applications that provide a fail-safe state. The termination of flows might be triggered if the promised guarantees cannot be further maintained or higher priority flows are requested. The objective of this paper is, however, to avoid the cancellation of flows comprising mission-critical applications.

Bidirectional communication can be implemented using two flows with opposing source/destination pairs.

IV. Introducing Mobility

In presence of mobile stations, the avoidance of network overload by admission control is much more challenging than in purely stationary networks. The resources required by a requested flow may severely vary, and thus increase, after the flow has been admitted. I. e., a flow f_S has been requested between two stationary nodes and was admitted by the CAM. Afterwards, a mobile station M requests another flow to a stationary node D. The current conditions in the network allow the acceptance of the second flow f_M, as the overall utilization is low since M and D are close to each other ($U = U_{f_M} + U_{f_S} \leq U_{max}$). However, when M starts moving within the network, the induced load may rise significantly. For instance, the real-world experiments presented in [10] show that the utilization induced by a video-stream to a mobile robot increases by up to three times during operation compared to the time the flow was requested. Consequently, the utilization induced by flows has to be modelled time dependent, as:

$$U_{f_M}(t_x) > U_{f_M}(t_0) \qquad \begin{array}{l} t_0 \mathrel{\widehat{=}} \text{time of request} \\ t_x \mathrel{\widehat{=}} \text{time after movement} \end{array} \tag{1}$$

The utilization induced by the stationary nodes may almost be invariant over time and thus can simply be considered as constant:

$$U_{f_S}(t_0) \approx U_{f_S}(t_x) \tag{2}$$

However, the overall utilization may lead to network overload:

$$U(t_x) = U_{f_M}(t_x) + U_{f_S}(t_x) > U_{max} \tag{3}$$

In this case, one of the flows has to be terminated to avoid that the QoS properties of the admitted flows may become violated. However, mission-critical applications cannot tolerate flow revocations issued by the admission manager – an admitted flow has to be maintained for its entire life time or it should not have been admitted at all.

To avoid the cancellation of mission-critical communication flows, the admission control has to be extended to provide dependable admission of communication flows even in case of mobility-induced network dynamics. The information whether a communication flow is safely interruptible or not must be provided on flow requests. Therefore, we define the following terminology:

- **Best-effort (BE) flow**: A flow that might be revoked by the admission manager after its admission at any time in order to avoid network overload.
- **Mission-critical (MC) flow**: A flow that, once admitted, must not be revoked by the admission manager. Only the application can release the flow.

In the following, we mainly focus on handling MC flows, as this is the new application class to be implemented.

The objective of a dependable admission that forbids the cancellation of MC flows implicates a trade-off between dependability and efficiency: To foster dependability, enough resources have to be reserved to be able to handle increasing capacity demands induced by station mobility. Those resource reservations may result in the rejection of additional MC flows. However, if or while the reserves are not required, the medium is not efficiently utilized. On the contrary, a more efficient utilization may jeopardize dependability and potentially force the cancellation of flows or otherwise impair the QoS. Indeed, the reserves for MC flows may be used by BE flows to improve the overall network efficiency.

A. Predictive Admission Control

If only BE flows are active, the present admission control scheme is sufficient: In case of imminent overload, some flows are canceled to ensure that the utilization stays below the defined limit. However, considering MC flows, an admission scheme has to foresee increasing capacity demands caused by station mobility. Thus, for the CAM it is not sufficient to only consider the present state of the network when a new flow is requested at time t_0. Instead, it should only admit new flows if the utilization is expected to stay below the limit for the entire time the flow may be active:

$$U(t) = \sum_i \hat{U}_{f_i}(t) \leq U_{max} \qquad \forall t > t_0 \tag{4}$$

whereas $\hat{U}_{f_i}(t)$ is an estimation function for the utilization induced by a flow f_i at an instant of time in the future.

In accordance with (2), the estimation for flows between stationary nodes may be approximated as constant:

$$\hat{U}_{f_s}(t) \approx U_{f_s}(t_0) \qquad f_s \text{ is stationary} \tag{5}$$

However, this requires that the CAM has knowledge about which nodes are stationary and which are mobile. Additionally, environmental dynamics may also cause variations with regard to the capacity requirements of a distinct flow.

For mobile stations, methods to estimate future capacity requirements and predict the utilization induced by a flow during its life-time have to be elaborated. In the present paper, instead of estimating the utilization at a definite instant of time $t_x > t_0$ as outlined in (4), we try to find an upper bound $\hat{U}_f$ for the utilization that is expected to be reached during the life-time of a flow f. By the reservation of sufficient resources to handle this upper bound of the utilization for the flow, we allow the provision of QoS guarantees even when mobile stations move and thus cause increasing capacity demands.

To reserve sufficient resources for MC admissions in presence of mobility, it is important that the upper bound for the overall utilization of all MC flows stays below the defined limit. Thus, whenever a new MC flow is requested, the admission manager needs to ensure

$$\hat{U}=\sum_f \hat{U}_f < U_{max} \tag{6}$$

If this is valid, the new flow is admitted, otherwise it is rejected. Accordingly, we need a way to determine $\hat{U}_f$. Note that this may sound simple and there are solutions for cell-based networks, it is much more challenging in wireless mesh networks, as the effect of mobility is more complex: Due to self-interference on a multi-hop path both the present utilization and the network capacity may change on movement.

In the following, we propose two approaches to determine an upper bound utilization that is considered for mission-critical mobile applications: The first approach determines the worst case while the second approach uses observations of the maximum utilization from the past.

B. Worst case: longest possible path

Without any restrictive assumptions about the mobility of the stations, we first consider a worst case approach: Whenever a flow is requested to or from a mobile station, we take into account that the station may move to any place in the covered area. This means it may happen that the station is only reachable via the most distant router in the network. Thus, when determining the worst case as upper bound for the utilization ($\hat{U}_f = U_f^{wc}$), we have to consider the utilization on the longest possible path.

In general, the following four conditions may be present when a flow from S_f to D_f is requested:

1) Both stations are stationary
2) S_f is stationary, D_f is mobile
3) S_f is mobile, D_f is stationary
4) Both stations are mobile

In case 1), U_f^{wc} is modelled according to equations 2 and 5 to be invariant in time and thus corresponds to the present condition.

For 2), we need to find the path to the most distant mesh router of all mesh routers R, i. e. the path with highest cost. The actual utilization on this path is considered as constant like in case 1) and depends on the source S_f, the last stationary router D_x, and the requested load L_f. Furthermore, we need to add an upper bound utilization for the last hop from D_x to D_f, which could be a predetermined constant based on the slowest modulation scheme of the present network.

$$U_f^{wc} = \max_{D_x \in R} \left(U(S_f, D_x, L_f)\right) + \hat{U}_{hop}(L_f) \tag{7}$$

As path costs may be asymmetric, we need to distinguish case 2) and 3), however, both are modelled similarly. For the latter case, we take a constant cost for the first hop and need to find the longest path from an arbitrary router to the actual destination:

$$U_f^{wc} = \hat{U}_{hop}(L_f) + \max_{S_x \in R} \left(U(S_x, D_f, L_f)\right) \tag{8}$$

Finally, for case 4), we also need to consider the worst case: both mobile stations are at the end points of the longest path in the network, thus we take the utilization of two hops plus that of the longest path:

$$U_f^{wc} = 2 \cdot \hat{U}_{hop}(L_f) + \max_{S_x \in R, D_x \in R} \left(U(S_x, D_x, L_f)\right) \tag{9}$$

This approach should lead to a dependable admission control: If a MC flow to or from a mobile station is requested, it is only admitted, if the utilization will be beneath the limit even if the station moves to the most distant place in the network and thus induces the maximum possible utilization. However, as this is a pessimistic approach considering the worst case, the medium would not be used very efficiently: If a station moves only within a small operation area, it may never cause such a high utilization as assumed in this model. Flow requests may be rejected, as not enough resources for the longest possible path are available – even though much less resources may be sufficient in the present case.

C. Maximum utilization observed in the past

The previous approach allows for a dependable admission control for mission-critical applications by reserving sufficient resources for the worst case. However, considering the presence of BE flows in the network as additional redundancy may allow for a less pessimistic estimation of an upper bound for the utilization of MC flows. Thus, our second approach considers the maximum utilization observed in the past to determine the upper bound for present MC flow requests.

For this purpose, we introduce the notion of a *job*: Considering mobile industrial applications, we assume recurrent mobility patterns, e.g. a transport vehicle that carries goods to a machine or products from a machine to a warehouse. These jobs are distinct applications running on mobile platforms and also comprise the request of a distinct communication flow. We assume that such a job can be identified by a job id, which is passed as additional parameter during flow requests.

We further define subsequent application runs of a certain job j as tasks $T_{j,1} \ldots T_{j,n}$. To estimate an upper bound based on past observations of the maximum utilization induced during a task, the admission manager monitors the utilization induced by the flow of a task $T_{j,i}$ and logs its maximum value:

$$U_{T_{j,i}}^{max} = \max_{t_{T_{j,i}}^{req} \leq t < t_{T_{j,i}}^{rel}} \left(U_{T_{j,i}}(t) \right) \tag{10}$$

where $t_{T_{j,i}}^{req}$ and $t_{T_{j,i}}^{rel}$ are the flow request and release time of the task $T_{j,i}$, respectively.

The admission manager maintains a list of observations of the maximum utilization for the last n tasks for each job id. Whenever a flow is requested by a new task $T_{j,x}$, the upper bound for the utilization is the maximum value of the maximum utilization observed for the last n tasks of job j:

$$\hat{U}_{T_{j,x}} = \max_{i=(x-n)\ldots(x-1)} \left(U_{T_{j,i}}^{max} \right) \tag{11}$$

The value n may be defined dependent on the expected grade of variance in the application: A low value tends to underestimate the maximum utilization, as only few values are considered. However, a large value results in a lower adaption rate to changed conditions: E. g., if the mobility pattern of a job changes in a way that lowers the observed maximum utilization, the estimate for the present task tends to overestimate the utilization. For this work we set $n = 5$. An additional series of experiments regarding this approach of tracking the capacity demands for future reservations can be found in [11].

For the first task of a job, i. e. if there is no history present to be used for estimating the maximum utilization, the admission manager may fall back to the previous worst-case approach. This allows to log the maximum utilization for the first task of a job and use this for subsequent tasks.

This approach uses observations of the maximum utilization from the past to estimate the upper bound for a present flow request. While this is more resource efficient than the previous worst-case approach, some under-estimations may occur. However, we consider this approach to only be applied if the present network utilization also comprises BE flows. These can be cancelled to compensate an underestimated utilization.

V. Evaluation

Our main objective is to introduce a dependable admission control scheme for the new class of mission-critical mobile applications, which avoids the cancellation of previously admitted MC flows due to over-utilization. To show that we reached this objective will be subject of our first evaluation.

However, the medium should also be utilized efficiently, i. e. as many MC flows as possible should be admitted. E. g., one extreme is simply to not admit any flow. While this would avoid cancellation, it is obviously inadequate. The acceptance of flows if the *present* utilization allows it, would efficiently utilize the medium, but cause a high rate of cancellations and thus cannot serve MC applications. So the second objective is to increase the efficiency of the medium

Parameter	Value
Standard	IEEE 802.11g
Transmission power	16 dBm
Frequency	2.412 GHz
Path loss exponent (β)	5.7
Shadowing deviation (σ_{dB})	4 dB
Reference distance	1 meter
Rate control algorithm	minstrel

Table I: Simulation Parameters

utilization for MC flows without sacrificing dependability. This should be shown by comparing the two approaches previously described: the worst case assumption that a node may only be reachable via the most distant router (longest path, section IV-B) and the estimation of the maximum utilization using previous tasks (maxUtil, section IV-C).

Finally, we will show that the overall network utilization is not decreased if both MC and BE flows are present and that the existence of BE flows does not impair the dependability of MC admissions.

We implemented both methods in the central admission manager (CAM) that runs on top of AWDS[1], an open-source implementation of a link-state WMN routing protocol. An abstraction layer [6] allows us to use the same implementation of the routing protocol in real networks as well as in simulated networks. However, for the sake of reproducibility and comparability, the evaluation is performed using the network simulator ns-3.

The Wifi devices on all nodes have been configured to use the IEEE 802.11g standard with parameters shown in table I and operate in Ad-Hoc mode. The propagation of signals is modelled according to the shadowing model by composing the log-distance loss model and the random loss model built into ns-3. The parameters for these models were set to correspond to a path loss exponent of $\beta = 5.7$ and a shadowing deviation of $\sigma_{dB} = 4$. These values were obtained from measurements in our faculty building and are used for comparability with future experiments.

When comparing the two approaches with each other and with the original non-predictive scheme, a series of artificially generated scenarios is used. For comparability, in each scenario all variants are evaluated with the same initial conditions. The stationary routers are placed in a square grid topology of 3 x 3 routers. Ten mobile nodes, which operate within this area, are initially placed randomly. One of the stationary nodes also functions as the CAM.

The mobile nodes are controlled by an application that mimics the behavior of transport vehicles in industrial environments. When a mobile node is idle, it randomly chooses one of 10 randomly generated jobs. The description of a job contains a list of 2 to 5 randomly placed waypoints which the mobile node is supposed to move to. The number

[1]https://ivs-pm.ovgu.de/projects/awds – Ad-Hoc Wireless Distribution Service

of waypoints adds to the variation of the length of the paths, but has no further influence in our evaluation. The job description also specifies the parameters of a flow that is required to be available during execution of the job. Every job has a unique id which will be provided when requesting the flow. The bandwidth required for the job is randomly chosen from the range between 1600 and 3000 kbit/s. The bandwidth and the number of mobile nodes have been chosen to generate a sufficient load for the evaluation while having only a minimum number of mobile nodes idling due to limited capacity.

Mobile stations first move to the starting point of the given path. Then, each station requests the assigned flow and, on admission of the flow, it follows the path. One endpoint of the flow is the mobile node itself, the other one is one of the stationary nodes. If at any time the flow is terminated due to over-utilization, the stations stops moving and tries to re-request the flow to continue its work.

While a mobile station in the scenario described above will eventually succeed in performing its job when it is able to regain the terminated flow, the production process it is involved in will be affected negatively. Not only has the job been delayed but the mobile node might also come to a stop in an unfavourable location where it interferes with other mobile nodes in the operating area.

A. *Dependable Admission for MC flows*

First, we compare the proposed approaches regarding the dependability of the admission of MC flows, i. e. the ability of the admission control mechanism to maintain admissions even in presence of station mobility. We simulated 20 different scenarios for 30 minutes each and recorded how often a previously admitted flow is cancelled. Figure 2 shows for each variant the number of cancellations relative to the number of flows admitted. The line in the middle represents the median, the box the first and third quartile and the whiskers the minimum and maximum over all simulation runs. For comparison, we also show the results for the case that no prediction is used.

As expected, when the CAM does not consider the future utilization at the time of a request, it has to cancel between 12% and 40% of the previously admitted flows later on. This includes events where a flow has to be cancelled multiple times before a mobile station is able to complete its job. On average 63 of 204 admitted flows had to be cancelled, what shows that MC applications cannot be handled if mobility is not considered.

When using the estimation based on the longest path, the CAM never cancels previously admitted flows, because it overestimates the utilization caused by the flow. However, as a consequence, only 33 flows have been admitted on average in each scenario.

When using the maximum utilization of previous tasks to predict the utilization of a flow, in some scenarios the CAM

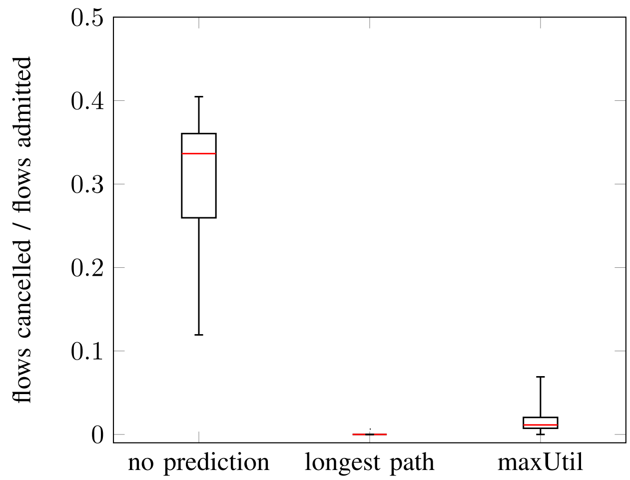

Figure 2: Ratio of Flows Cancelled to Flows Admitted

never had to cancel an admitted flow. In other scenarios up to 7% of all admitted flows had to be terminated. On average 88 flows have been admitted and in more than half of the scenarios only up to one flow had to be terminated. If a flow had to be terminated, most of the time it happened in the first few minutes of that simulation run. This is to be expected because there is no information about previous tasks. When a station requests a flow that has not been previously seen, for this evaluation the CAM uses the optimistic approach and admits it if the present utilization allows it. If later on the utilization exceeds the maximum allowed value, one of the active flows will be cancelled. While in a real setup we consider BE flows to be present and could be cancelled to compensate the increased resource requirements, the evaluation only comprised MC flows. When a station releases a flow, the maximum utilization for this task is logged and will be considered for subsequent tasks.

B. *Efficiency of Resource Reservation*

In this section we evaluate the efficiency of the resource reservation for the presented methods. As the present approach estimates an upper bound and respectively reserves the maximum of the expected resource requirements, it trades efficiency for dependability. To quantify the efficiency we compare the number of completed MC jobs from the previously described scenarios.

Figure 3 shows the number of MC jobs that completed without interruption for different network sizes. As the size of the network grows, longer routes are possible and flows may cause a higher utilization or a higher variance as more links are involved. We simulated scenarios with 4, 9, 16 and 25 routers in a square grid. We performed 20 simulations lasting 30 minutes for every combination of network size and variant.

The results show that the estimation based on the max-

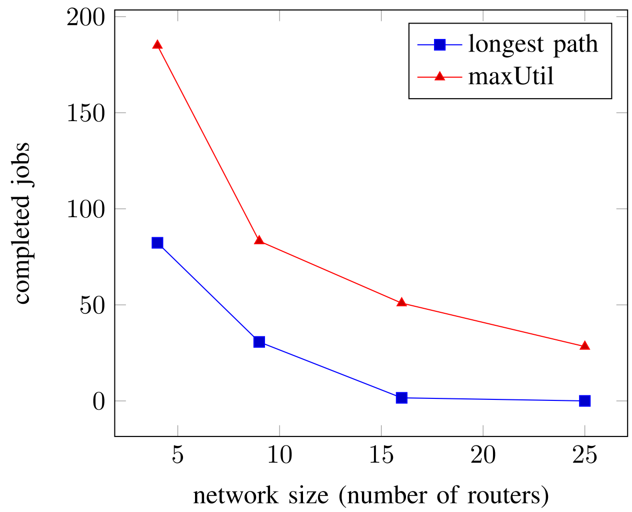

Figure 3: Number of Completed MC Jobs

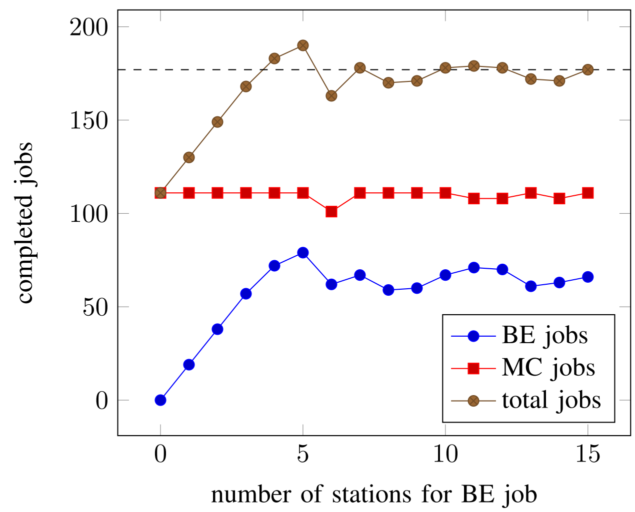

Figure 4: Network Efficiency With BE and MC Flows

imum utilization of previous tasks outperforms the worst-case approach of considering the longest path. In particular, the latter is only able to complete any jobs in the 4 and 9 router network. With 16 routers only very few and with 25 routers no flows were accepted at all. As explained in section IV-B this is to be expected in large networks because in the worst case high bandwidth requirements cannot be fulfilled anymore. The less pessimistic estimation based on previous maximum utilizations reserves fewer resources and thus is able to allow more MC jobs in parallel. The available resources are thus much better utilized and the efficiency is increased.

C. *Overall Network Efficiency with BE and MC Flows*

Finally, we want to evaluate the co-existence of both BE and MC flows. The price to be paid for a dependable admission of MC flows is that resources have to be reserved to allow the movement of a station after the initial admission. However, if besides the MC flows also BE flows are present within the network, the remaining capacity as part of the reserve can be utilized for BE traffic. I. e. as long as the MC flows do not entirely exploit their reserved resources, BE flows can be admitted and are maintained while the actual utilization in the network allows for it. Hereby, the BE flows should not impair the MC flows.

We setup an experiment with only two jobs – one of them requires an MC flow and the other one requests a BE flow. At first, there are only three mobile stations running the MC job. In each of the 15 successive simulation runs, one station is added running the BE job.

Figure 4 shows the respective results in terms of the number of completed jobs for both BE and MC jobs as well as the total number of completed jobs. It can be seen that the number of completed MC jobs is almost constant and independent of the number of BE jobs running. The number of completed BE jobs increases almost linearly with the number of stations up to 5. More running stations cannot further increase the job completions, as the network is saturated. However, even in saturation the processing of MC jobs is not impaired.

The total number of completed jobs approaches a value that is marked with a dashed line. This value has been measured in a slightly adapted experiment where both of the jobs were BE jobs and thus represents a benchmark for the maximum number of job completions. Thus it can be concluded that if BE and MC jobs coexist, the overall network efficiency is not reduced even though a dependable admission for MC jobs requires the reservation of resources to handle mobility.

VI. Conclusion

This paper elaborates an approach for dependable admission control for mission-critical mobile applications in Wireless Mesh Networks. The fundamental challenge is to handle the network dynamics imposed by station mobility. In general, an admission control mechanism reserves resources to provide certain QoS guarantees to applications. While it is already challenging to determine the amount of resources required to maintain a certain QoS, the mobility of stations exacerbates the problem: It is not sufficient to consider the present conditions within the network, as those may change after a flow is admitted. A flow to a mobile station may require increasing resources as the station starts to move. Thus, an appropriate admission control mechanism has to foresee and consider network dynamics expected from station mobility.

In this paper, we proposed two approaches to determine an upper bound for the utilization that is expected to be induced by a new flow. By reserving respective resources, we provide a dependable admission control scheme that is able to maintain admissions also in presence of mobile stations. Thus, the main contribution is the introduction of a new class of guarantee for mission-critical mobile applications. The first approach considers the longest possible path as a worst case assumption. It thus is highly dependable but lacks of efficient network utilization. Our second estimation method is based on observations of the maximum utilization of previous tasks and provides a significantly better efficiency in terms of an increased number of admitted flows. If both mission-critical and best-effort flows are active, the network can be fully utilized without decreasing its dependability.

Our future work will further elaborate on the approach of predictive admission control for mobile stations. We will consider learning algorithms from data mining to find corresponding tasks even if they do not account for a distinct job id. Additionally, instead of only estimating the maximum utilization, we will learn the progression of the utilization during the movement of a mobile station. By these means, we expect to be able to find a schedule for the resource allocation that allows to further improve the efficiency of the network utilization for mission-critical applications without sacrificing dependability.

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