QoC-based Optimization of End-to-End M-Health Data Delivery Services

Ing Widya, Bert-Jan van Beijnum, Alfons Salden

***Abstract*—This paper addresses how Quality of Context (QoC) can be used to optimize end-to-end mobile healthcare (m-health) data delivery services in the presence of alternative delivery paths, which is quite common in a pervasive computing and communication environment. We propose min-max-plus based algebraic QoC models for computing the quality of delivered data impeded by the QoS of the resources along the alternative delivery paths. The constructed algebraic structures in those models directly relate to the resource configurations represented as directed graphs. The properties of the applied algebras correspond to the properties of the operations of the addressed QoS dimensions. To rank all the possible resource configurations and therewith select from those the most optimal one(s) we introduce a workflow management metric based on the quality dimensions like freshness and availability. We focus on the pre-establishment phase of m-health data delivery services; dynamic QoC issues existing during service execution are not considered.**

***Index Terms*—algebraic computational models, mobile healthcare, QoC, QoS, service composition.**

I. INTRODUCTION

INTERNET Service Providers (ISPs) do not only bring ubiquitous interconnectivity to (users of) networked applications, but also offer alternative network connections of different (wireless) technologies and qualities. Advancement in pervasive computing further enables discovery and selection of computational nodes and (wireless) connections of required quality. Together, these developments enable services or applications to adapt to the operational contexts to meet the needs or preferences of the users [1].

In the application domain of mobile healthcare (m-health), for example, Electrocardiogram (ECG), oxygen saturation and physical activity signals of a patient enrolled in a rehabilitation care program may be monitored in real-time by a physiotherapist during an indoor or an outdoor exercise of the patient [2], [3]. The supervising physiotherapist may use these signs, typically together with the patient's medical history (e.g. health record), as context data to remotely control the exercise by providing advices to increase or decrease the level of intensity of the exercise or to stop the exercise. Rendering the vital signs timely and reliably improves the loop of control of the remotely guided exercise. In a pervasive computing and communication environment, the quality of the context data (QoC) [4] as required by the therapist to control the exercise optimally, depends on the discovered and selected resources used to realize the delivery and the rendering of the data. For example, it depends on the technology of the available (wireless) network links discovered and their quality of services (QoS), cf. [4].

The above m-health example illustrates the need for a robust methodology to select the right configuration of resources amongst alternatives aiming to optimize the provisioning of services in meeting the user's requirements. The example also indicates the prospect of QoC to improve context data delivery services and, in particular, to adapt the operational behavior of the context using applications.

In this paper, we investigate how quality of context can be computed to enable selection of resource configurations for end-to-end m-health context data delivery, such that the delivered QoC meets the quality requirements of the context applying applications or the context-aware services. Accordingly, we also investigate how QoC depends on the QoS of the computational and communication services expected from or realized by the resources along the context data delivery chain. We propose algebraic computational models for several quality dimensions, each of them based on the configuration of the system's resources (i.e. the processing units and (wireless) communication links) along the end-to-end context data delivery chain. In this way, the applied algebras provide a common computational technique for the concerned quality dimensions. That is, the properties of the applied algebra correspond in an isomorphic sense to the properties of the operations of the addressed quality dimensions. Additionally, we propose a workflow management based method to solve the problem of optimizing the multidimensional metric of computed quality dimensions brought by the independent use of the computational models for the concerned QoC dimensions.

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To illustrate the computational models we elaborate on the freshness, availability and cost QoC dimensions for a sensor-based m-health data delivery service. Herein we focus on the pre-establishment phase of the end-to-end data delivery service; that is, we focus on the set-up of a service. As such, QoC computation during service execution to adapt to changing context quality is beyond our scope.

The problem of optimizing chains of resources with specific QoS or quality of device (QoD) measures [4] is a well studied shortest path problem in network routing. An algebra for network routing has been proposed in [5]. The constructed algebra is based on the weights of the edges of the underlying directed graph of routing nodes. It also applies operations of a min-plus algebra, which itself is often used for solving minimum path problems [6], [7]. Max-plus algebras, on the other hand, are also used for synchronization of path routes, such as in (train) transportation networks [7]. Relations between these (dioid) algebras can be found in [8].

Similar to the approach applied in [5], reliability analysis and evaluation techniques have evolved around the concept of constructing a reliability model from the system under consideration, and then formulate, define and analyze the system reliability. A good overview of the various modeling techniques is given in [9] and the relationships among these modeling techniques are discussed in detail in [10]. Reduced Ordered Binary Decision Diagrams have been applied in several reliability studies [11], in the context of fault analysis or reliability in large-scale industrial applications.

A context data delivery chain, which involves alternative configurations of resources, is quite static in the considered pre-establishment phase, it can effectively be viewed as a workflow. A workflow for delivering a service has also been represented as a graph [12]. Furthermore, on a space of workflows one has proposed to construct or empirically model either a cost measure, or a workflow metric [12] in order to capture both network performance and selection criteria for launching the right control flow measures.

This work is inspired by the applications of the max- and min-plus algebras, in particular in network routing but it extends to min-max-plus algebras to include the sensory based m-health monitoring operations.

Accordingly, this paper is organized as follows. Section II describes a sensor-based context data delivery chain consisting of alternative resource configurations for m-health applications. On these resource configurations, we define a context flow graph (Section III). We describe the algebraic computational models which are based on the context flow graph for those quality dimensions which satisfy the properties of the applied algebras. To illustrate the use of the computational models we compute freshness, availability and (monetary) cost QoC dimensions in our m-health scenario in Section IV. In this section, we also apply a workflow metric to compute an optimal resource configuration for the scenario. The final section contains our conclusions and future work.

II. A MOTIVATING M-HEALTH EXAMPLE

We demonstrate the importance of our QoC computational models within the m-health domain. Thereto, we consider the rehabilitation scenario used in [2], [3] and discussed in the introduction. In this scenario, ECG, oxygen saturation and physical activity signs of a patient are monitored in real-time during daily indoor or outdoor exercise sessions. The exercises have a duration between 30 and 60 minutes. The vital signs are transferred from the various sensors attached to the patient's body via Front-Ends, a Mobile Base Unit (MBU) and an m-Health Portal (mHP) to the therapist (Fig. 1). The applied m-health monitoring system is developed and used in the MobiHealth [2] and HealthService24 [3] projects and is further extended with context-aware services in the project Awareness [13]. The system is based on the notion of mobile Body Area Networks (BANs) [14], [15], a network of body worn sensors, actuators and light-weight computational and communication devices. A Front-End of a MobiHealth BAN aggregates, filters and multiplexes the different vital sign data streams originating from the sensors. In the abovementioned scenario, there are two different Front-Ends: one for the physical activity signals and the other to aggregate the vital signs ECG and oxygen saturation. Each Front-End transfers its vital sign data towards the MBU via BlueTooth [16], or alternatively via another short range wireless technology like ZigBee [17]. The MBU also acts as a gateway of the BAN to forward the vital signs via Internet to the Back-End system of the m-Health Portal. This MBU may select a communication link of a Public Network Operator (PNO) of type WiFi (802.11), GPRS or UMTS [16] to reach the Back-End system on the Internet. In case of an indoor exercise, the MBU may additionally route the data transfer via a home WiFi and the modem of an ADSL home gateway connected on an Internet Service Provider.

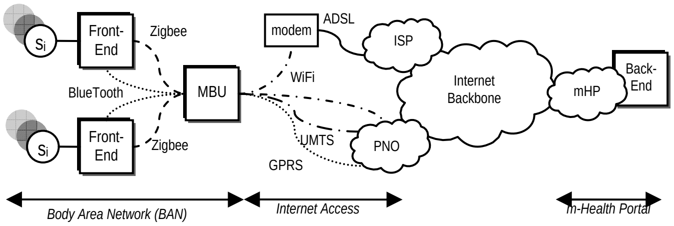

Fig. 1. Awareness mobile vital sign acquisition and monitoring system.

The measured vital signs arriving at the different components of the monitoring system are raw context data. The freshness QoC dimension, which indicates the degree of up-to-dateness of the raw context data, is different at each point in the data delivery chain (i.e. from sensors to the Back-End). Typically, the freshness of the vital sign data arriving at the different components degrades along the context data delivery chain and the amount of degradation depends on the latency of the processing units and the delays of the communication links along the context data delivery path.

In the illustrated context data delivery chain, one can identify three types of operations, which are relevant for the QoC computational models:

- Aggregation: synchronized merge of (raw) context data;
- Preselect: selection of alternative resources (e.g. processing units or communication links) during the pre-establishment phase of the context data delivery service;
- Concatenation: hand-over of (raw) context data between subsequent components.

Aggregation of m-health data like a patient's vital signs comes from the need to use these signs collectively as an indicative approximation of a single, possibly complex, physiological phenomenon. In typical cases, the aggregated context data should be treated as atomic units of interpretation (e.g. to capture medical episodes). The QoS of the in-between processing units and the communication links influences the QoC of the synchronously aggregated m-health data. The selection between BlueTooth and ZigBee (Fig. 1) for example, is an infrastructural capability, which is independent of the application data interpretation, but with an impact on the quality of data and therefore it indirectly influences the contextual use of the data.

Since our focus is on the pre-establishment phase of services, we may assume without losing generality that concatenations distribute over preselect operations. This means that a context data delivery path preceding a choice between communication or computation alternatives is equivalent to a choice (i.e. preselect) between the path concatenated by either one of the alternative segments. This property is also valid during service execution if the alternative resources are independent. However, this distribution property is in general not valid for the aggregation operations due to the higher demand on resources in the aggregated case.

In the next section, we make use of this distribution property and we specify the basic building blocks of the context data delivery chain that originate from the three abovementioned operations. We also determine the QoC computational elements of each of the QoC dimension.

III. QOC COMPUTIONAL MODELS SERVING WORKFLOW MANAGEMENT

Similar to the models used in the algebraic QoS path computation [5], we use a directed graph to represent the resource configuration, which forms the logical structure underlying the context data delivery chain (cf. Fig. 1). The bottom part of Fig. 2 depicts the elementary structure of the directed graph of a resource configuration and the upper part the elementary relation between QoC of context data at element A and at element B, as well as the QoS of the processing unit or communication link between these elements. This figure therefore is an illustration of how QoC in typical cases degrades along the context data delivery chain.

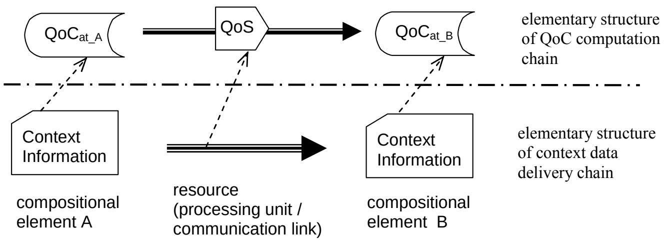

Fig. 2. QoS impedes QoC_{at_A} at the compositional element B

The nodes of the directed graph therefore represent the compositional elements on which context data flows. The edges of the graph represent the resources (i.e. the processing units and communication links), by which the context data delivery flow is impeded. Accordingly, we call this graph the context flow graph.

A. Context Flow Graphs

The context flow graph discussed here is similar to a workflow graph but simplified in the types of the compositional elements, i.e. it has a smaller set of node types [18], [19]. The graph contains multiple labeled edges between two nodes in case alternative communication links are able to convey context data or alternative threads are able to process the data. In this functional perspective, a node in the context flow graph represents the concatenation followed by the preselect operation described in Section II, unless the node is a sink. A sink node is a terminal point at which context data is eventually available for instance for further use in the pervasive computing and communication environment. We therefore consider the selection of a single edge without other competing alternatives as a trivial preselect operation. A subsequent node is also required to accept the preselect. We further define nodes that additionally represent the aggregation operation. These nodes aggregate (raw) context data before forwarding the aggregated data. We furthermore define source nodes to represent context data generators (e.g. vital sign sensors). These nodes specify the boundary conditions of the context flow and QoC computational models.

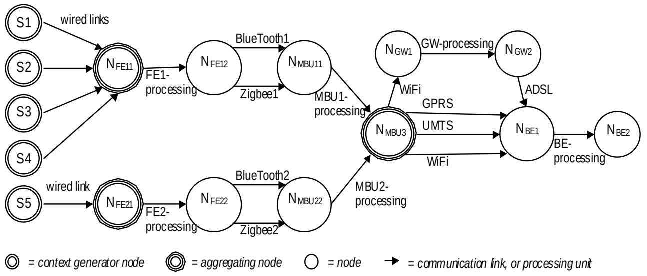

Fig. 3. Context flow graph of the data delivery chain for the indoor exercise

Fig. 3 shows the context flow graph of the vital sign data delivery chain from the sensor sets to the Back-End system of the m-Health Portal for the indoor exercise case (see Fig. 1).

The Front-Ends are decomposed into two types of nodes, i.e. N_{FEi1}, i=1,2, which are data aggregators, and N_{FEi2}, i=1,2, denoting the nodes that forward data either via a BlueTooth or a ZigBee link to the MBU. In turn, this MBU is decomposed into three nodes of which N_{MBU3} is a data aggregator.

B. QoC computational models

In this section, we describe the generic elements of our algebraic QoC computational models that represent the elements of the quality dimensions (e.g. freshness or availability) including the compositional operations of these elements. These elements are associated with the elements of the context flow graph, i.e. the resources and the compositional operations like preselect, aggregation and concatenation (see Fig. 3 and Fig. 2). The properties of the algebras applied therefore define the scope of the quality dimensions that are suitable for the QoC computational models discussed in this paper. In this way, the applied algebras provide a common computational technique for the concerned quality dimensions.

A computational model for optimal selection of routes of concatenated paths can be based on a min-plus algebra (viz. [5] – [7]). This algebra consists of two operations. The first corresponds to the selection of the shortest (minimal cost) path and the second operation corresponds to the summation of the quality dimension elements of concern (e.g. the quality dimension delay), in the case of path concatenations. Synchronized aggregation or synchronization of routing elements can also be solved using a max-plus algebra [7]. This algebra is similar (i.e. isomorphic) to the min-plus algebra, but with the first operation of the algebra semantically associating with the longest or the worst-case selection.

Given our type of QoC problems, particularly in respect of the three operations described in Section II, we propose QoC computational models, which apply min-plus, max-plus or jointly min-max-plus algebras. We briefly introduce the generic min-plus and max-plus computations necessary for QoC computations.

1) Generic Min-plus computation

As explained above, a min-plus algebra [6] constitutes two binary operations, the so-called additive and the multiplicative operations denoted by $\oplus$ and $\otimes$, respectively. The common semantic of the additive operation is the arithmetic minimum and the common semantic of the multiplicative operation is the arithmetic summation. These semantic mappings are valid for the freshness QoC dimension. We typically have the following relations: $a \oplus b \overset{\Delta}{=} min\{a,b\}$ (addition) and $a \otimes b \overset{\Delta}{=} a+b$ (multiplication).

Conform the literature, we do not distinguish between the notations of the element *a* or *b* that belongs to the left hand side (e.g. the algebra of (symbolic) elements representing the elements of a quality dimension like freshness) or the right hand side algebras (e.g. the arithmetic of the measures (/values) of the elements of the quality dimension addressed at the left hand side, e.g. freshness).

Accordingly, we construct the min-plus structure $\langle S,\oplus,\otimes,I_\oplus,I_\otimes,0_\oplus,0_\otimes \rangle$. This structure is a closed semi ring with S denoting a set of (symbolic) elements of the concerned quality dimension. The operations $\oplus$ and $\otimes$ are the previously defined binary operators, which are closed in S. The special elements $0_\oplus, I_\oplus \in S$ denote the annihilator (/null) and the identity elements in respect of the additive $\oplus$ operator, respectively. Analogously, $0_\otimes, I_\otimes$ denote the annihilator and the identity elements in S in respect of the multiplicative $\otimes$ operator, respectively. The special element $0_\otimes$ can also be viewed as a representation of a special quality element (e.g. a special delay element) associated to a virtual edge between nodes of the context flow graph that are not interconnected by an application meaningful processing unit or communication link. This edge represents a resource which completely impedes the concerned QoC dimension. It could, for example, represent a communication link with infinite delay or zero availability. Analogously, the special element $I_\otimes$ could be considered a representation of a special element of the quality dimension of concern, associated to a resource of zero delay or 100% availability.

We further have the associative property of the $\otimes$ and $\oplus$ operators and the property that $\otimes$ distributes over $\oplus$. That is, $\underset{x,y,z\in S}{\forall} (x*y)*z = x*(y*z)$ with $*$ denoting either the $\otimes$ or the $\oplus$ operator, $\underset{x,y,z\in S}{\forall} (x\oplus y)\otimes z = (x\otimes z)\oplus(y\otimes z)$, and the left side $\otimes$ distribution equation.

Instead of using scalar expressions to present our QoC computations, we use a matrix notation for representational convenience. This notation is often used in dynamic cases where the elements of *S* are time or event series.

Example: Let the delay of the BlueTooth link be d_b and the one of ZigBee be d_z. The freshness (*Fr*) of the vital sign set at the node N_{MBU1} (Fig. 3) can be computed using a min-plus relation from the data freshness at the moment it resides at the node N_{FE12}:

$$Fr_{MBU1} = \begin{bmatrix} I_\otimes & I_\otimes \end{bmatrix} \begin{bmatrix} d_b \\ d_z \end{bmatrix} Fr_{FE12} = (d_b \oplus d_z) \otimes Fr_{FE12}$$

with Fr_{MBU1} and Fr_{FE12} denote the freshness of the data at the earlier mentioned nodes. In the arithmetic domain, this semantically translates to $Fr_{MBU1} = \underset{i\in\{b,z\}}{minimum}\{d_i\} + Fr_{FE12}$.

2) Generic Max-plus computation

A max-plus algebra [6] is isomorphic to the min-plus algebra; it differs in one respect, in that the additive operator represents the arithmetic maximum operator. The max-plus algebra has the same properties as the min-plus algebra presented above.

To distinguish between the different operators of the two algebras, as well as the identity and the annihilator elements, we augment the postfix subscript "$_{max}$" to the operators and elements of the max-plus algebra if necessary, to avoid ambiguity. Similarly, in the matrix notation we explicitly use the matrix multiplication symbol $\bullet_{max}$.

Example: Let the delay of each wired link on vital sign sensors *S1* and *S2* be d_0, then the freshness of the vital signs at a Front-End *FE* is

$$Fr_{FE} = \begin{bmatrix} I_{\otimes} & I_{\otimes} \end{bmatrix} \bullet_{max} \begin{bmatrix} d_0 & 0_{\otimes} \\ 0_{\otimes} & d_0 \end{bmatrix} \begin{bmatrix} Fr_{S1} \\ Fr_{S2} \end{bmatrix}$$

$$= (d_0 \otimes Fr_{S1}) \oplus_{max} (d_0 \otimes Fr_{S2}).$$

In the arithmetic domain this semantically translates to $Fr_{FE} = \underset{i=1,2}{maximum} \{d_0 + Fr_{Si}\}$

C. *QoC sensitive workflow management metrics*

As discussed earlier, the context data delivery process in a pervasive computing and communication environment is very much associated with the selection, adjustment, and execution of a workflow (*W*), an ordered and coordinated in-time composition $\Diamond$ of a set of functions $\{\gamma_i \mid i = 0, \ldots, i_{max}\}$ realized by resources reserved at a suitable location and time, (x_i, t_i). Each W depends on a tuple of inputs $\{I_{ij_i} \mid j_i = 1, \ldots, j_{i_{max}}\}$ arriving in-time; thus

$$W = \gamma_0 [(x_0, t_0), \{I_{0j_0}\}] \Diamond \ldots \Diamond \gamma_{i_{max}} [(x_{i_{max}}, t_{i_{max}}), \{I_{i_{max} j_{i_{max}}}\}],$$

such that it meets the requirements as expressed in e.g. a Service Level Agreement [4].

In general, the functions $\{\gamma_i \mid i = 0, \ldots, i_{max}\}$ involve storage, computing, and communication as well as application and service composition. However, we can simplify the previously discussed workflow expression and interpretation in the context of delivery of m-health related context data. The delivery chain contains context data aggregation functions and alternative paths of context data delivery from context data generators at the sensors to the context data delivery sink (Fig. 1). Moreover, our focus on the pre-establishment phase of context data delivery services makes the workflow more static. The functions $\{\gamma_i \mid i = 0, \ldots, i_{max}\}$ furthermore represent all possible context data delivery paths instead of mere individual resources at a specific location within the context data delivery service.

Analogues to the context flow graph, we link each workflow W with a set of QoC dimensions (cf. Fig. 2). In general, QoC dimensions are incommensurable, they cannot be compared, nor compete during workflow management of context data delivery services. For example, if availability of the data is maximal for a specific path, then the freshness of the data may be suboptimal not to say minimal.

In order to solve such workflow management conflicts, a metric weighing the (not necessarily independent) QoC dimensions involved in a workflow can be useful. Inspired by van der Aalst [12], we resolve such conflicts with a suitable cost measure Ω on the space of workflows. Resulting in the following workflow management metric: $\Omega(W) = \Omega\{\gamma_0 [\{I_{0j_0}\}] \Diamond \ldots \Diamond \gamma_{i_{max}} [\{I_{i_{max} j_{i_{max}}}\}]\}$. It serves as a slot machine taking workflows on resource configuration topologies as input, and producing a related cost measure as output. Note that the composition operator $\Diamond$ in the workflow W translates into a QoC dimension specific integral operator in the workflow management metric. Furthermore, the operation of computing this metric is equivalent to the second operation occurring in the min- and max-plus algebras, i.e. the operation which corresponds to the summation of the quality dimension elements of concern in case of path concatenations.

Let Ω_i be the measure of the QoC dimension "*i*". Now we may propose the following context data delivery workflow management metric: $\overline{\Omega}(W) = \sqrt{\sum_i w_i^2 \Omega_i^2 (W)}$, with w_i service specific weights. Such a metric may be given extensive accounts only after empirical modeling the workflow management and the context data delivery services. A metric in line with empirical model will then be defined by the characteristics and performances of the underlying resource topologies involved in the potential context flow graphs [12].

In the following section, we apply a workflow metric in the selection of the optimal path for the m-health data delivery.

IV. APPLICATION TO M-HEALTH DATA DELIVERY PROBLEM

The desired quality of the delivered data for a particular purpose requires optimization of various and often conflicting QoC values. In the following, we point out the applicability of our QoC computational models and their usage to determine, in the pre-establishment phase, the optimal workflow. More generally, we rank the solutions realizing the end-to-end data delivery service. In particular, we calculate in advance the freshness, availability and (variable monetary) service costs of communication networks influencing the QoC of the delivered vital sign data. Thereafter, we show how ranking and selecting the optimal paths of the addressed context flow graph can be achieved using a workflow metric.

We base our computations on the vital sign data delivery scenario shown in Fig. 3. Herein ECG and plethysmogram (for deriving oxygen saturation) data collected by sensors $S1$, $S2$, $S3$ and $S4$, and activity data collected by sensor $S5$ are sent via wired links for aggregation and further processing to Front-End N_{FE12} and N_{FE22}, respectively. After this, the two different data streams are sent for processing over either Bluetooth or ZigBee links to N_{MBU1} and N_{MBU2}, respectively. The combined data streams are send for processing either over GPRS, UMTS, WiFi, or WiFi&ADSL to the Back-End N_{BE1}, which after additional processing reaches N_{BE2}.

Finally, we combine our computational models for freshness, availability and service costs into a context-sensitive workflow metric to find the path that has the smallest QoC impeding value.

To keep our illustration simple, we neglect the impeding influences of the computing units and only consider the QoS influences of communication links in the computation of QoC.

For many m-health scenarios, the bandwidth requirements are often moderate. Table 1 shows the various parameters settings of an already high quality vital sign monitoring system for the rehabilitation scenario discussed in Section II. It shows that the estimated bandwidth requirements can be fulfilled by all access technologies used in our scenario. The traffic volume estimate is based on the assumption that two 30 minute exercises are executed every day.

To illustrate the applicability of the QoC computational models with a numerical example, we use the parameter values shown in Table 2. The values for the delay of various communication channels and their availability are purely exemplary. For the monetary costs, we entirely focus on the variable costs, hence flat fees for service subscriptions, and acquisition costs (e.g. for PDA hosting the MBU) are left out of the cost considerations. The values listed show the additional monthly costs for the specific access technology. These values are based on readily available commercial product offerings. As an example, UMTS data services are offered today for a flat fee of 75 Euro with 1 GB free data transfer (and 0.25 Euro/MB for excessive traffic), given the monthly data volume for the scenario we have monthly incremental costs of zero. The costs of other access technologies have been derived in the same way.

TABLE 1: SENSOR AND TRAFFIC CHARACTERISTICS

Vital Sign	#Sensors	Sampling frequency [samples/s]	Sample size [bits/sample]	Compression factor	Data rate [Kbps]	Required bandwidth [(a)] [Kbps]	Traffic volume[(b)] [MB/month]
Plethysmogram/O_2Sat	1	128	24	1	3	3,3	44,1
ECG	3	512	24	0,5	18	19,8	264,7
Mobility	1	128	8	1	1	1,1	14,7
Total					22	24,2	323,5

(a) A protocol overhead of 10% is assumed, this number is based on trial data in the MobiHealth project (cf. D3.1 deliverable in[2]).

(b) Traffic volume is a monthly average, and based on two exercise sessions per day.

TABLE 2: ASSUMED PARAMETER VALUES FOR SCENARIO EVALUATION

	GPRS	UMTS	WiFi	WiFi+ADSL	ZigBee1	BlueTooth1	Zigbee2	BlueTooth2
Delay [ms]	5	4	3	1	7	10	4	8
Availability	0,990	0,985	0,980	0,999 | 0 (1)	0,96	0,97	0,96	0,97
Costs [€] (2)	418	0	260	0	0	0	0	0

(a) In the presence of the WiFi+ADSL, the availability is 0.999 (i.e. the indoor case); in the outdoor case the WiFi+ADSL is assumed unavailable.

(b) The costs represent variable costs per month, based on the scenario under analysis.

A. Freshness Dimension

The computational model for the freshness QoC dimension applies the min-max-plus algebra which joins the min-plus and the max-plus algebras, introduced in Section III.B. As discussed earlier, this model aims to identify the alternative paths (i.e. alternative sub-trees of the context flow graph in case of data aggregations) of the context data delivery chain and it also aims to express on each alternative the freshness of the context data at the Back-End node given the freshness of the raw sensory data at the sensor sets. Due to the aggregation of sensor data in the context data delivery chain, each expression of freshness on an alternative path configuration has to contain the max-plus additive $\oplus_{max}$ operations. That is, the $\oplus_{max}$ operations are encapsulated before additive min-plus $\oplus$ operations within the matrix expression of the freshness at the Back-End node. In our elaboration of the freshness expression, we therefore apply the distributive equation $\oplus_{max}\left(\bigoplus_{\forall i} a_i, \bigoplus_{\forall j} b_j\right) = \bigoplus_{\forall i}\left(\bigoplus_{\forall j}\left(a_i \oplus_{max} b_j\right)\right)$, which comes from the property that $\oplus_{max}$ distributes over $\oplus$ in the min-max-plus algebra. This equation can be easily verified since $\oplus_{max}$ and $\oplus$ translate to the maximum and the minimum operations in the arithmetic domain, respectively.

Let d_g, d_u, d_w, d_{wh} be the delay of the wireless access link GPRS, UMTS, WiFi and the combination of WiFi and ADSL via the home gateway, respectively (see also Fig. 3). Furthermore, let $d_{z1}, d_{z2}, d_{b1}, d_{b2}$ be the delays of the ZigBee and BlueTooth links for each Front-End, respectively. Then, after some variable substitutions, matrix multiplication and transposition as well as by applying the distributive equation discussed previously, but applied in the matrix notation, we get the following (partially shown) expression for the freshness of the context data at the Back-End node given the freshness at the sensors for the indoor exercise case (Fig. 3):

$$Fr_{BE2} = \begin{bmatrix} I_{\otimes} & I_{\otimes} & I_{\otimes} & I_{\otimes} \end{bmatrix} \begin{bmatrix} d_g \otimes (d_{z1} \otimes Fr_{FE11} \oplus_{max} d_{z2} \otimes Fr_{FE21}) & .. & .. & .. \\ d_u \otimes (d_{z1} \otimes Fr_{FE11} \oplus_{max} d_{z2} \otimes Fr_{FE21}) & .. & .. & .. \\ d_w \otimes (d_{z1} \otimes Fr_{FE11} \oplus_{max} d_{z2} \otimes Fr_{FE21}) & .. & .. & .. \\ d_{wh} \otimes (d_{z1} \otimes Fr_{FE11} \oplus_{max} d_{z2} \otimes Fr_{FE21}) & .. & .. & .. \end{bmatrix} \begin{bmatrix} I_{\otimes} \\ I_{\otimes} \\ I_{\otimes} \\ I_{\otimes} \end{bmatrix}$$

with

$Fr_{FE11} = d_{wl1} \otimes Fr_{S1} \oplus_{max} d_{wl2} \otimes Fr_{S2} \ldots \oplus_{max} d_{wl4} \otimes Fr_{S4}$, $Fr_{FE21} = d_{wl5} \otimes Fr_{S5}$, and d_{wli} representing the delay of the wired link from sensor *Si* to the Front-End.

In the formula, the delays of the processing units are assumed to be zero. The elements of the 4x4 matrix represent the alternative paths of the context data delivery. For example, the first row first column element of the matrix represents the path which uses the ZigBee links after both Front-End nodes and the GPRS link between the MBU and the Back-End. The second column of the matrix contains similar expressions as the first column but with the delays of the ZigBee and BlueTooth as selected technology after the first and the second Front-Ends, respectively. Analogously, the third column contains expressions for the selection of BlueTooth and ZigBee for Front-End1 and Front-End2. The last column contains the alternatives over the BlueTooth connections.

B. *Availability*

In accordance with our chosen approach, reliability analysis traditionally constructs a reliability model from the system under consideration and then formulates, defines and analyzes the system's reliability probabilities. We use a two state failure model. That is, any resource (e.g. a processing unit or a communication link) in the addressed pre-establishment phase is either considered to be available or not. We do not consider repairs because they are not relevant in the concerned pre-establishment phase. The availability measure we consider here is the steady state availability as defined in [9], and we assume that all availability elements of resources (processing units and communication links) are mutually independent.

Traditionally, reliability analysis is performed directly in the domain of probability values, based on tree structures and has an assumption similar to the one formulated above; deviations have traditionally been resolved by developing and using estimations. A more rigorous analysis method capable of taking dependencies among entities into account without requiring estimations is based on Boolean functions. These latter are used to capture the entity sets determining the reliability of the composite system. Reduced Ordered Binary Decision Diagrams (ROBDD) can be used as an effective and, in many cases, efficient representation of such Boolean functions. The ultimate probabilistic value is then computed, based on Shannon expansion and a valuation function ([10]). For our problem at hand, where we have a true tree structure for our context provisioning chain and resource independence, we resort to the traditional analysis.

In the availability computations, the concatenation operation maps to the arithmetic multiplication of the availability probabilistic measures, the preselect maps to the arithmetic maximum operation of the availability probabilistic measures and the aggregation maps to the multiplication of availabilities. Hence, in computation of availability for our scenario, we basically have a <max, *> algebra, which is isomorphic to the min-plus algebra [8]. Without going into the mathematical details of the inferences, the availability (*Av*) of the context data delivered at node N_{BE2} in our scenario is:

$$Av_{BE2} = \begin{bmatrix} I_{\otimes} & I_{\otimes} & I_{\otimes} & I_{\otimes} \end{bmatrix} \bullet_{max} \begin{bmatrix} a_g \otimes ((a_{z1} \otimes Av_{FE11}) \otimes (a_{z2} \otimes Av_{FE21})) & \ldots & \ldots & \ldots \\ a_u \otimes ((a_{z1} \otimes Av_{FE11}) \otimes (a_{z2} \otimes Av_{FE21})) & \ldots & \ldots & \ldots \\ a_w \otimes ((a_{z1} \otimes Av_{FE11}) \otimes (a_{z2} \otimes Av_{FE21})) & \ldots & \ldots & \ldots \\ a_{wh} \otimes ((a_{z1} \otimes Av_{FE11}) \otimes (a_{z2} \otimes Av_{FE21})) & \ldots & \ldots & \ldots \end{bmatrix} \bullet_{max} \begin{bmatrix} I_{\otimes} \\ I_{\otimes} \\ I_{\otimes} \\ I_{\otimes} \end{bmatrix}$$

Here Av_{FE11} and Av_{FE21} denote the availability of context at the nodes N_{FE11} and N_{FE21} respectively. In line with the assumptions in the freshness computation case, it has been assumed that the availability of MBU-processing and BE-processing is 1. The rows and columns identify the same paths as those for the freshness. Note that in this matrix, the ⊗ maps to the arithmetic multiplication of the availability probabilistic measures.

C. *Service Cost*

A third quality dimension considered here is the (monetary) costs associated to the context service provisioning. Assuming the case where the transfer of vital sign data from the MBU to the Back-End system uses either the wireless access or ADSL technologies discussed previously, the purpose here is to minimize the total communication costs per time interval for the different sessions on a monthly basis.

For the computation of costs, both concatenation and aggregation map to the arithmetic addition, and the preselect maps to the arithmetic minimum operation. In other words, the costs quality dimension is in fact a min-plus algebra over resource costs. Applying this algebra to our scenario, the total service costs (*Co*) at the Back-End are:

$$Co_{BE2} = \begin{bmatrix} I_{\otimes} & I_{\otimes} & I_{\otimes} & I_{\otimes} \end{bmatrix} \begin{bmatrix} c_g \otimes ((c_{z1} \otimes Co_{FE11}) \otimes (c_{z2} \otimes Co_{FE21})) & \ldots & \ldots & \ldots \\ c_u \otimes ((c_{z1} \otimes Co_{FE11}) \otimes (c_{z2} \otimes Co_{FE21})) & \ldots & \ldots & \ldots \\ c_w \otimes ((c_{z1} \otimes Co_{FE11}) \otimes (c_{z2} \otimes Co_{FE21})) & \ldots & \ldots & \ldots \\ c_{wh} \otimes ((c_{z1} \otimes Co_{FE11}) \otimes (c_{z2} \otimes Co_{FE21})) & \ldots & \ldots & \ldots \end{bmatrix} \begin{bmatrix} I_{\otimes} \\ I_{\otimes} \\ I_{\otimes} \\ I_{\otimes} \end{bmatrix}$$

As explained in Section III, we will focus on the variable costs of the resources. Moreover, in the example that will be further detailed in the next section, we assume the (variable monetary) costs of the Front-End related resources and the

Back-End resource to be equal to zero. Hence, in effect the costs that are taken into account are the wireless access or ADSL costs.

D. QoC sensitive hierarchy of context flow graphs

Using our exemplary QoC dimensions from the previous sections, we have the following data delivery workflow management metric $\overline{\Omega}$ (see section C):

$$\overline{\Omega}(W) = \sqrt{w_{Fr}^2 \Omega_{Fr}^2 + w_{(1-Av)}^2 \Omega_{(1-Av)}^2 + w_{Co}^2 \Omega_{Co}^2} \ .$$

Note that the metric is based on the unavailability (i.e. *1-Av*), as to assure that a metric is constructed in which the dimensions have equal "direction", see e.g. the QoS specification language QML [19] which uses a similar construct. In this weighted multidimensional optimization, the best path of the context data delivery chain need not be the optimum, considering just the freshness, the availability or the service cost QoC only.

Using the values listed in Table 2, the Quality dimensions of Freshness, Availability and Costs for the paths are given by the following three matrices, respectively,

$$Fr_{BE2} = \begin{bmatrix} 12 & 13 & 15 & 15 \\ 11 & 12 & 14 & 14 \\ 10 & 11 & 13 & 13 \\ 8 & 9 & 11 & 11 \end{bmatrix},$$

$$Av_{BE2} = \begin{bmatrix} 0.91238 & 0.92188 & 0.92188 & 0.93149 \\ 0.90777 & 0.91723 & 0.91723 & 0.92678 \\ 0.90316 & 0.91257 & 0.91257 & 0.92208 \\ 0.92067 & 0.93026 & 0.93026 & 0.93995 \end{bmatrix}, \text{ and}$$

$$Co_{BE2} = \begin{bmatrix} 418 & 418 & 418 & 418 \\ 0 & 0 & 0 & 0 \\ 260 & 260 & 260 & 260 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

As an example, we assume that the weights have been assigned the following (not normalized) values: $w_{Fr} = 1, w_{1-Av} = 150, w_{Co} = 0.02$. Of course, such weights need to be accounted for in a deployment phase; the right metric has to be modeled empirically. Such model may imply that for the data delivery optimization problem at hand one or more QoC dimensions can be irrelevant.

Resorting to the weight given above, Fig. 4 (a) shows the output of the metric for the indoor case, and (b) shows that for the outdoor case, where the availability of the WiFi&ADSL is zero. In the indoor case, the most optimal data delivery path for the given quality dimension weights uses ZigBee after Front-End1, BlueTooth after Front-End2 and the home gateway route. The most optimal path for the outdoor case traverses the same BAN segment but uses UMTS instead of the home gateway route.

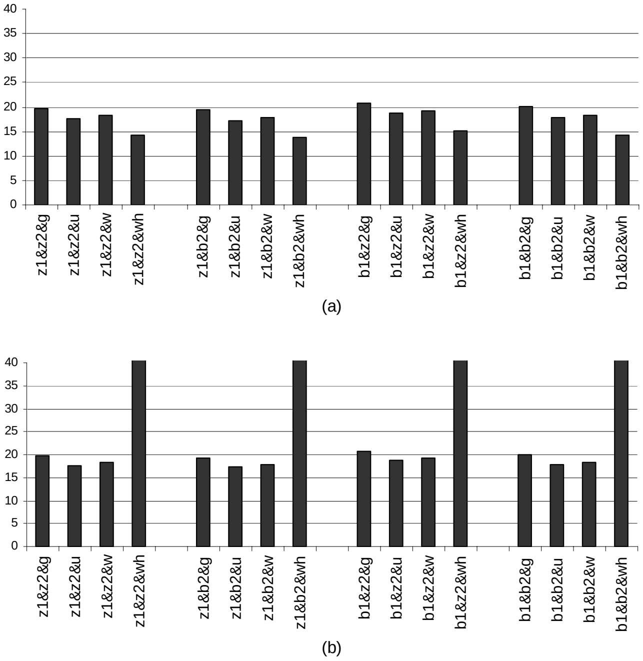

Fig. 4. The QoC metric of the data delivery chain: a) indoor; b) outdoor

V. CONCLUSIONS AND FUTURE WORK

We addressed QoC from a service infrastructural perspective and proposed algebraic computational models for several QoC dimensions, each of them based on the configuration of the system's resources along the context data delivery chain. The min-plus algebra was used for the cost dimension, the max-plus algebra for the availability dimension and the min-max-plus algebra for the freshness dimension. We also illustrated the use of a workflow management metric amalgamating the multi QoC dimensions in determining optimal data delivery chains among alternative ones. The examples further illustrate how QoC can be used to improve the delivery of context data such that the quality requirements of the context using applications or context-aware services can be met. The min-max-plus algebra (in which the min-plus and max-plus algebras are special cases) provides a common technique for the computational models of the investigated QoC dimensions.

In this paper, we focused on the pre-establishment phase of end-to-end context data delivery services. Dynamic QoC computations during service execution in a pervasive computing or communication setting are left for future work. For the dynamic cases, we intend to reuse the min-max-plus algebras, within which the elements are then time or event series. Another research direction is to relax the assumption that the QoC impeding QoS of a resource is independent of the load of the resource, therefore taken the so-called quality of device into account. This assumption can be put forward for the pre-establishment phase, but does not necessarily hold for the service execution phase.

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REFERENCES

[1] M. Satyanarayanan, "Pervasive Computing: Vision and Challenges", *IEEE Personal Communications,* pp. 10 – 17, August 2001;

[2] MobiHealth, "MobiHealth project IST-2001-36006", "Detailed description of trial scenarios (D1.3)" and "Trial ready GPRS and UMTS networks (D3.1)", EC programme IST, 2002, http://www.mobihealth.org, visited Feb. 24th 2006;

[3] HealthService24, "HealthService24 project eTEN-C517352", 2005, EC eTEN Programme, http://www.healthservice24.com, visited Feb. 24th 2006;

[4] T. Buchholz, A. Küpper , M. Schiffers, " Quality of Context: What it is and why we need it", *Proceedings of the Workshop of the HP OpenView University Associations 2003 (HPOVUA2003)*, Geneva, 2003;

[5] J.L. Sobrinho, "Algebra and Algorithms for QoS Path Computation and Hop-by-Hop Routing in the Internet", *IEEE/ACM Transactions on Networking*, (10)4, August 2002, pp. 541 – 550;

[6] C.G. Cassandras and S. Lafortune, "Introduction to Discrete Event Systems", Kluwer Academic Pub., 1999;

[7] B. Heidergott, G.J. Olsder, and J. van der Woude, *Max Plus at Work: Modeling and Analysis of Synchronized Systems: A Course on Max-Plus Algebra and its Applications,* Princeton University Press, 2006;

[8] S. Gaubert et al., "Methods and Applications of (max,+) Linear Algebra", *14th Symposium on Theoretical Aspects of Computer Scienc*e, Lübeck, Germany, Feb. 27-Mar. 1st, 1997;

[9] J.K. Muppala, R.M. Fricks, K.S. Trivedi, "Techniques for Dependability Evaluation", in *Computational Probability*, W. Grasman (ed.), Kluwer Academic Publishers, 2000, pp. 445-480;

[10] M. Malhotra, K.S. Trivedi, Power-Hierarchy of Dependability-Model Types, *IEEE Trans. on Reliability*, Vol 43 (2), Sep. 1994, pp. 493-502;

[11] A. Rauzy, "New Algorithms for fault trees analysis", *Reliability Engineering and Safety Systems*, Vol. 40, 1993, pp. 203-211;

[12] W.M.P. van der Aalst and K. van Hee; *Workflow Management: Models, Methods, and Systems*, Cambridge: MIT Press, 2002;

[13] Awareness, "AWARENESS: Context Aware Mobile Networks and Services", Dutch Freeband Communications Research Program, http://awareness.freeband.nl, visited Feb. 24th 2006;

[14] T. Zimmerman, "Wireless networked digital devices: A new paradigm for computating and communication", IBM System Journal, 38(4), 1999;

[15] D. Konstantas et al., "Mobile Patient Monitoring: The Mobihealth System", the *Journal on Information Technology in Healthcare*, vol. 2(5), 2004;

[16] J. Schiller, "*Mobile Communications*", Addison—Wesley, 2003;

[17] Zigbee Alliance, "Wireless control that simply works", http://www.zigbee.org/en/index.asp;

[18] W.M.P. van der Aalst, "Workflow Patterns", *Distributed and Parallel Databases*, 14(3), pp. 5 – 51, Kluwer Acad. Pub., 2003;

[19] M.C. Jaeger, G. Rojec-Goldmann, and G. Mühl, "QoS Aggregation for Web Service Composition using Workflow Patterns", *Proceedings of the 8th IEEE Intl. Enterprise Distributed Object Computing Conf. (EDOC'2004),* pp. 149-159, 2004;

[20] S. Frølund and J. Koistinen, "Quality-of-service Specification in Distributed Object Systems", *Distributed Systems Engineering*, 5(4), Dec. 1998, pp. 179-202;