

Wireless Network Resource Management for Web-Based Multimedia Document Services

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ABSTRACT

Recent advances in wireless technology and availability of portable devices with networking capabilities have enabled ubiquitous Web accessibility. This has created the need to provide advance Internet services to mobile users without causing service failures due to connection migration or handoffs. However, scarcity of wireless resources restricts the provision of multimedia services in wireless networks. In this article we address the issue of managing wireless resources to support Web-based multimedia document services including MPEG-4-based applications, in wireless networks with a high degree of user mobility. In particular, we formulate the resource management problem in wireless networks as an optimization problem with an objective function comprising different quality of presentation parameters.

INTRODUCTION

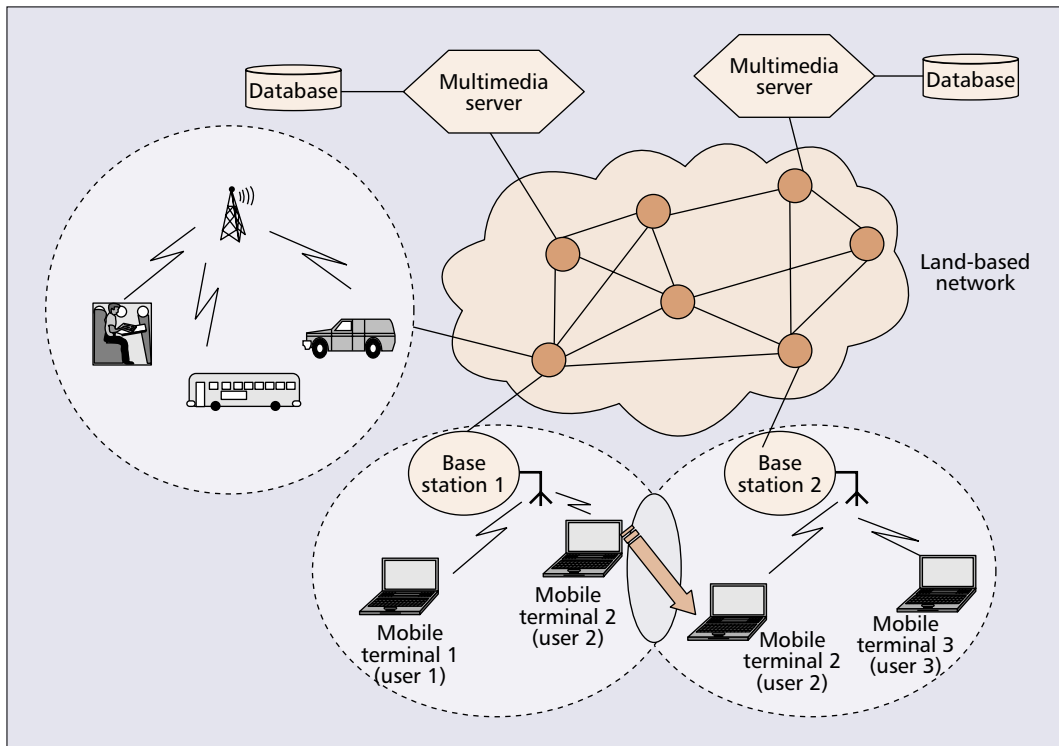
The existing wireless network infrastructure and communication protocols provide mobile users limited Internet-based services including Web browsing, short message service (SMS), and emails [1]. This is mainly because of the low bandwidth capacity and high error rates associated with wireless networks. However, with rapid advances in wireless technologies and the emergence of third-generation (3G) systems that can support data rates up to 2 Mb/s [1], the service spectrum for mobile users is being widened to include novel multimedia applications such as e-commerce, distance learning, videoconferencing, digital libraries, online TV/radio, and many others.

The future network system can be envisioned as a global network with a high degree of heterogeneity, providing advanced Internet services to users irrespective of their points of connectivity to the network. To accommodate mobile

users, a wireless network must provide continuous and mobility-independent connectivity. Mobility is a generic term and does not fully characterize users' roaming behavior. For instance, a stock broker can have high indoor mobility in a stock exchange building. On the other hand, commuters driving on interstate highways have long-range mobility, and passengers on a plane have global mobility. The future network system is expected to integrate all these levels of mobility and will provide ubiquitous access to users as depicted in Fig. 1.

The support of multimedia applications over a heterogeneous network requires communication protocols and networking infrastructure capable of providing high-quality services. Prior to connection establishment, such services need to specify connection requirements in terms of network resources, and the duration for which these resources are needed. Multimedia applications in general are not monolithic in nature, and can consist of several objects integrated together such as video clips, images, text, and audio segments. A multimedia application consisting of multiple objects can be represented as a multimedia document [2]. An example of a multimedia document is an MPEG-4-based application. MPEG-4 encompasses all types of media, and uses scene and object descriptors (SDs and ODs) to define the spatiotemporal features of the component media objects [3]. Figure 2 shows a collection of multimedia documents organized for a Web-based browsing environment. Typically, such an environment consists of a collection of documents or SDs for MPEG-4-based applications, integrated to allow random browsing by viewers.

In this article we consider resource management issues in supporting Web-based multimedia document services in a heterogeneous mobile networking environment shown in Fig. 1. In particular, we formulate the wireless resource management problem as an optimization problem



■ **Figure 1.** A heterogeneous wireless network with mobile users.

for which solutions can be developed and utilized in designing base stations for future mobile networks. Another key issue addressed in this article is mobility management of users as they roam from cell to cell, as depicted in Fig. 1.

NETWORKING CHALLENGES FOR MULTIMEDIA SERVICES IN MOBILE NETWORK

Conceptually, a multimedia mobile network is similar to a cellular communications system in which a given geographical area is divided into multiple cells. Each cell has its own base station that communicates with the mobile users in that cell on an RF channel. The base stations can be connected to a backbone land-based network consisting of high-speed routers/switches and multimedia database servers as depicted in Fig. 1 [4]. Like cellular phone systems, a user in this network can roam in any direction and migrate to any of the neighboring cells. Typically, the lifetime of a multimedia session involving browsing through the multimedia Web environment can be greater than the residency time of a mobile user in a single cell. In other words, a mobile user subscribing to a multimedia service in some cell is likely to migrate to a different cell during the session. In that case, the land-based route needs to be established to the new cell so that the multimedia session can continue. However, if sufficient RF bandwidth resources are not available in the new cell, the session may be terminated. To avoid such handoff failures, admission control and advance resource reservation must be performed based on the long-term availability of resources.

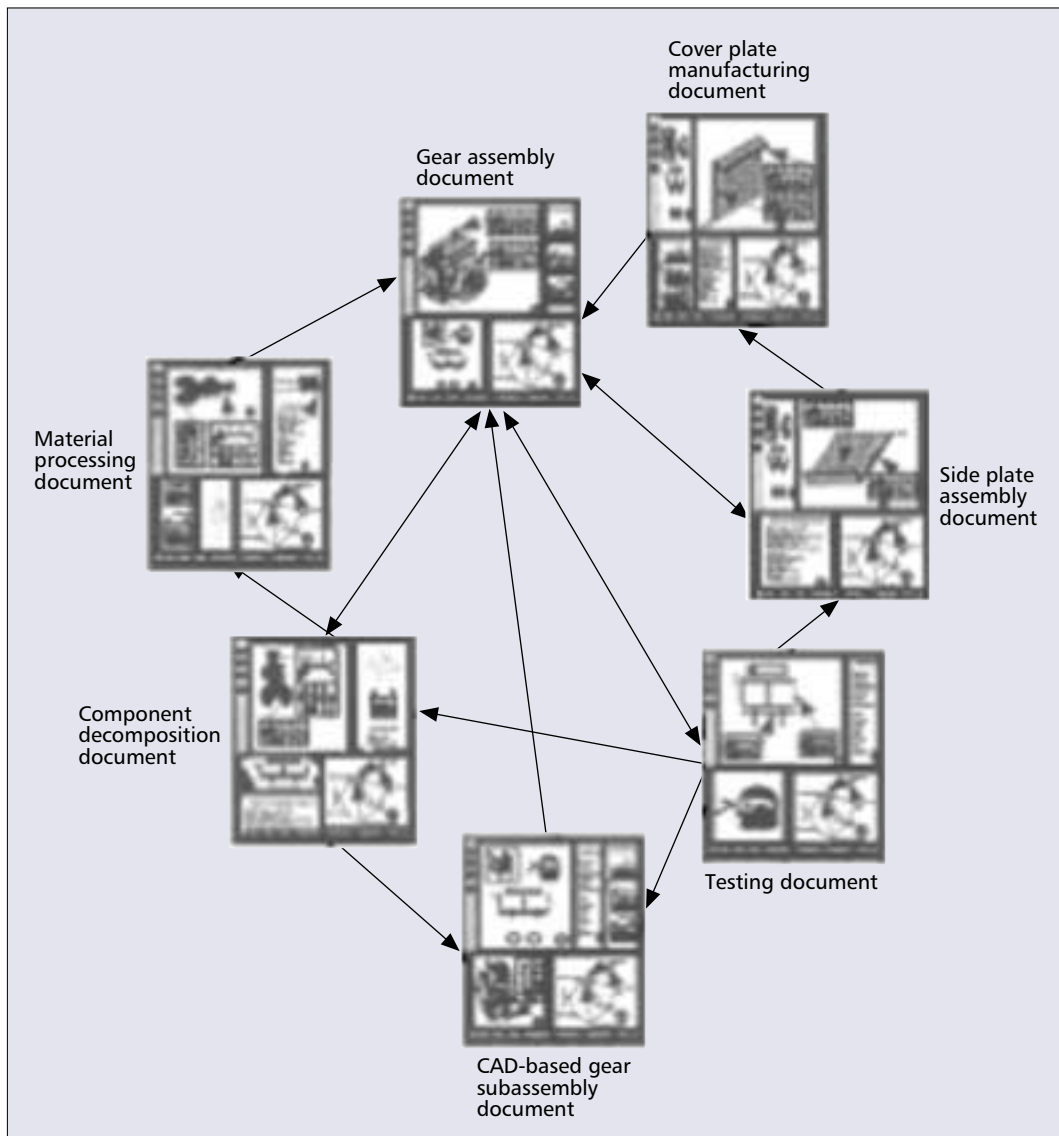
Another major challenge is the characterization of the bandwidth requirements of multimedia documents. Different objects such as video clips, text, and images in a multimedia document can have different bandwidth requirements. Depending on the concurrency level of objects, the quality parameters associated with individual multimedia objects, and the presentation duration of these objects, the overall bandwidth profile of a multimedia document may change considerably over a period of time. Accordingly, the resource requirements also vary. In order to provide quality-based multimedia services, the underlying network must accommodate such changes by allocating bandwidth resources in an efficient and timely manner.

MULTIMEDIA BANDWIDTH PROFILE

Traffic patterns generated in a multimedia Web environment are different from the traffic variations exhibited by a monolithic multimedia object such as a variable bit rate (VBR) video stream. In this case bandwidth variations are due to interframe compression. Object data streams generated by a multimedia document server, on the other hand, can have drastic variations due to the presence of multiple objects as well as due to random browsing of documents by a user, as depicted in Fig. 2. As mentioned earlier, document-level variations are due to changing levels of concurrency and characteristics of the component objects within the multimedia document. Figure 3a illustrates the bandwidth profile of a multimedia document represented as a node in the browsing graph of Fig. 2. Effective capacity approximation can be used to estimate the bandwidth profile at the object level. Objects within a multimedia document can generate diverse traffic patterns. Such approximation, however, can-

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To support multimedia document applications with guaranteed QoP, resources must be reserved at each node along the land-based route, and the base stations that serve as an interface between the land-based network and mobile users.



■ **Figure 2.** A browsing graph of multimedia.

not fully characterize document-level variations. In addition, bandwidth variations at the browsing level are the most difficult to characterize, as these variations are dependent on the random browsing activity by the user. In summary, the random nature of the browsing process, the changing level of concurrency, and the quality and time attributes of the component objects within a multimedia document result in a statistically varying workload.

Various document specification models, such as XML [5] and graphical models [2], exist in literature for specifying temporal, synchronization, and quality parameters for all objects in a document. One such model is object composition Petri-net (OCPN), which uses Petri-net-based formalism. Figure 3a shows OCPN specification of a multimedia document consisting of multiple objects with their temporal synchronization and presentation requirements. In addition, the model allows specification of quality of presentation (QoP) attributes specific to a particular object, as depicted in Fig. 3a. The QoP attributes may include resolution, frame rate, reliability,

and synchronization requirements. The reliability requirement specifies the maximum percentage of multimedia data that can be dropped if the allocated link capacity is limited. Synchronization is required for isochronous objects, such as audio and video, to have meaningful presentation. In addition to this interobject synchronization, intra-object synchronization is also needed to avoid any glitches and discontinuity in the playout process.

Given a document specification model, the bandwidth requirement of the component objects can be extracted by either using some effective bandwidth approximation method or specifying the peak and/or the average bandwidth requirement. The bandwidth profile, shown in Fig. 3b, can be stored in the document schema at the time of creation of a multimedia document [2, 4], and can be provided to the wireless network and end terminals at the time of connection establishment. Since the presentation schedule is available a priori, the wireless network can allocate resources efficiently by evaluating the bandwidth profile in a manner

that maintains the desired QoP within acceptable bounds. An example of such a scheme for a land-based network is described in [4]. This scheme relies on pre-orchestrated and prestored information for dynamic resource reservation.

USER MOBILITY

In a wireless network, the land-based route between the Web server and the wireless client may not remain fixed and can change with the movement of users across multiple cells, as depicted in Fig. 1. To ensure continuous delivery of multimedia objects to mobile users irrespective of their mobility patterns, dynamic admission control and resource reservation mechanisms can be used to establish land-based routes [4] from Web servers to all the cells a user may visit during the course of his/her session. The mobility pattern of a user can be estimated using the cell-specific or user-specific handoff history [6]. Admission control and resource allocation schemes that rely on mobility estimation keep an aggregate pool of resources (bandwidth, buffer) reserved for handoff connections, and can dynamically assign resources to migratory connections from this pool. This approach can support multimedia applications consisting of a single data stream whose traffic profile can be statistically characterized (e.g., a VBR video stream). However, for composite multimedia documents that have both object-level and document-level variations in their traffic patterns, this approach is not viable. Even for a single multimedia stream this approach does not guarantee zero handoff drops, as resources are not allocated on a per user basis [6].

A service model for mobile hosts in an integrated service packet network that offers zero handoff drops is presented in [7]. This model is based on the assumption that the mobility profile of a user is known a priori. A user specifies his/her traffic characterization and mobility profile at the time of connection request. Accordingly, the network allocates resources in all cells included in the user's mobility profile. In [8], an adaptive resource management scheme has been described that uses a range of values of bandwidth and delay. The network guarantees rate and jitter of admitted flows to remain within a specified range. Both of these schemes are designed for multimedia applications involving single media. These schemes, however, cannot manage multimedia connections for document communication where bandwidth and delay requirements vary significantly over longer periods of time.

RESOURCE MANAGEMENT FOR QOP-BASED MULTIMEDIA APPLICATIONS

To support multimedia document applications with guaranteed QoP, resources must be reserved at each node along the land-based route and the base stations that serve as an interface between the land-based network and mobile users. For simplicity of discussion, we assume that the land-based network is a

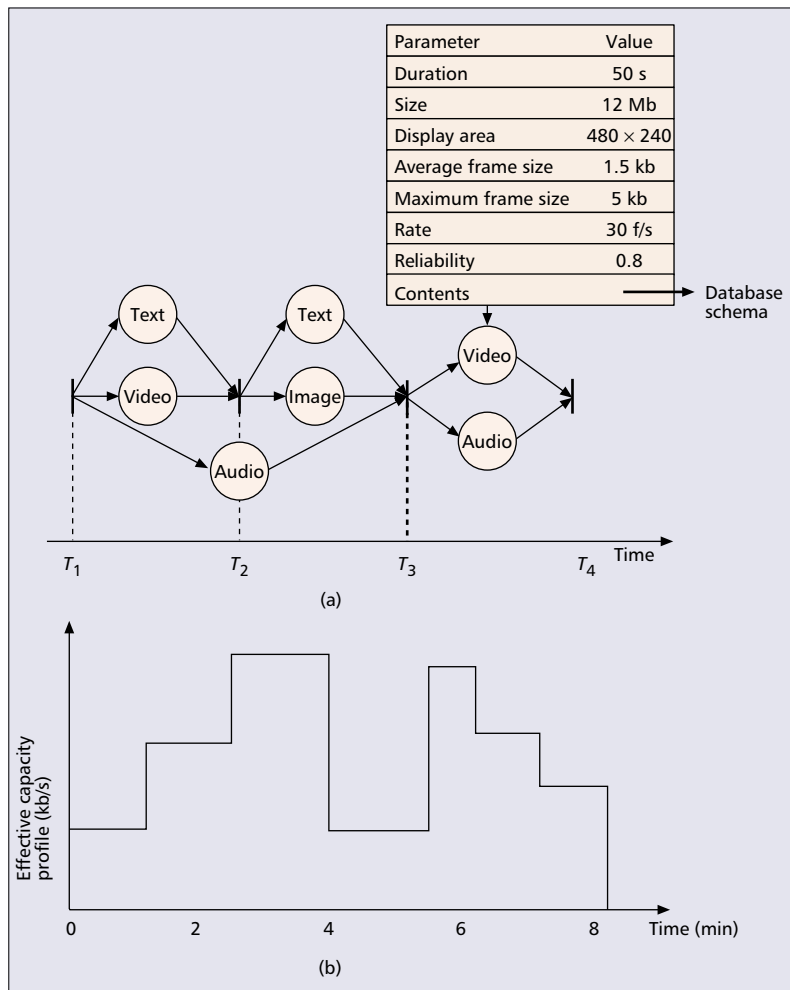
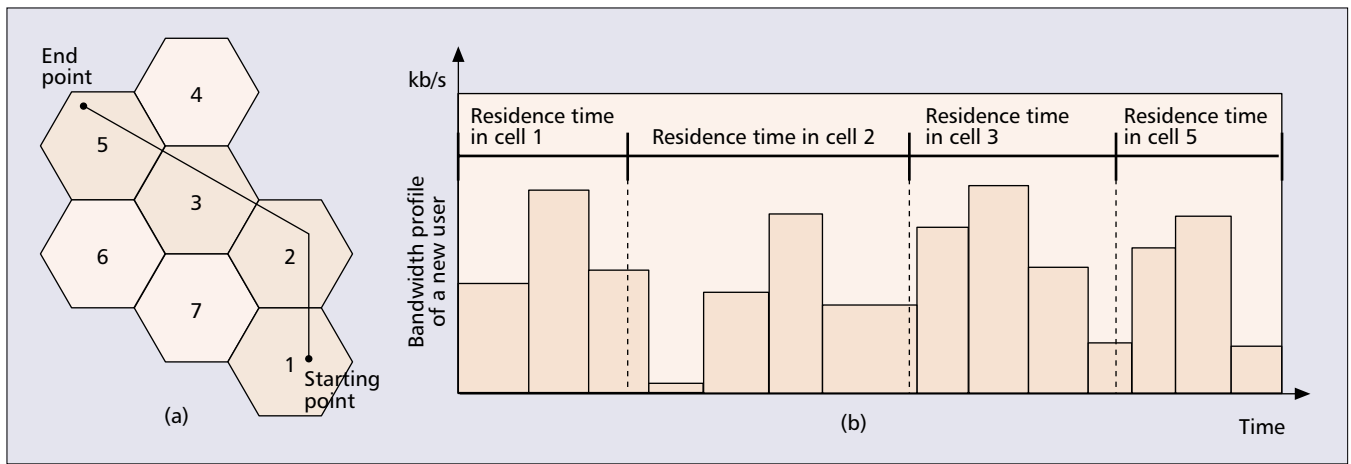


Figure 3. a) The effective bandwidth profile of a multimedia document; b) the OCPN representation of the multimedia document.

resource-sufficient system in the sense that it has enough resources to guarantee QoP required by the multimedia application. The resource management problem is then primarily confined to the base stations that transmit multimedia data to mobile users. We assume that the reverse channel from mobile user to base station is primarily used for communicating control signals for browsing and require negligible bandwidth.

To synchronize multimedia objects within a document, their data streams can be divided into fine-grained data units. The smallest unit is referred as a synchronization interval unit (SIU) [4]. For example, the synchronization interval for a video object can be taken as 1/30 of a second, which corresponds to the playout duration of a single video frame. For audio data, the smallest unit can be an audio sample.

For synchronization, one option is to cache enough multimedia data to compensate for a slower transfer rate. However, for mobile devices, providing a large buffer for multimedia data caching may not be feasible. Due to limited buffering capability and restricted bandwidth capacity at the base station, objects can be delivered partially by dropping some SIUs at the base station. For concurrent object data streams, determining the number of SIUs for



■ **Figure 4.** a) The predicted path of a mobile user; b) the bandwidth profile of the mobile user in the predicted path.

Cell id	Estimated residence time (mins)
1	18
2	36
3	24
5	20

■ **Table 1.** A user's mobility profile *M*.

each object to be dropped by the base station is equivalent to distributing some data reliability penalty among these objects. Criteria for such a decision can be based on the user's specified reliability parameter for multimedia objects. This parameter indicates the maximum acceptable loss of SIUs for different multimedia objects so that compensation for slow data streams can be provided.

TRAFFIC LOAD AT THE BASE STATIONS

The traffic load at each base station can change dynamically due to various factors such as the number of connections concurrently served by the base station, the changing level of concurrency of objects in a document, requests for new connections, and the migration of connections from/to other cells.

Newly originated connections are less sensitive to initial setup delay. Therefore, they can be handled in such a way that other ongoing sessions are not disturbed by them. Depending on the availability of RF channel bandwidth, the possibility of denying a new connection request cannot be ruled out. When a base station receives a request for a new connection, the request can be denied if sufficient bandwidth is not available to accommodate it without degrading the presentation quality of the already established connections beyond an acceptable level.

Another factor that determines the channel requirements at the base station is the migration of users among cells. In order to avoid handoff drops, the new cell must accommodate the migrating connection. One possible way to

handle a handoff connection is to treat it as a new connection request and invoke a bandwidth assignment procedure in the new cell. However, a migratory connection may be terminated if sufficient resources are not available. A viable solution to this problem is to reserve enough resources for mobile users in advance in all the cells to be visited by a mobile user during his/her connection lifetime. Advance reservation of resources in multiple cells for the entire duration of a multimedia session can be achieved using a priori information of the mobile user's arrival and departure times in each cell. Such a *mobility profile* of a user can contain estimated time of arrival and departure within a cell, using already known information such as the connection initiation point, size, structure, and geographical location of cells, and the maximum speed of mobile users. Reference [9] discusses a probability distribution function for the cell residence time for a mobile user. If the connection duration is assumed to be greater than the residence time in a single cell of radius R , and the mobile user is assumed to be travelling in a cell at a constant speed, which is uniformly distributed in the interval $[0, V_{\max}]$, the density function of the residence time T_R in the cell in which the connection is originated is given by

$$f_{T_R}(t) = \begin{cases} \frac{8R}{3V_{\max}\pi t^2} \left[1 - \sqrt{\left[1 - \left(\frac{tV_{\max}}{2R} \right)^2 \right]^3} \right] & \text{(a)} \\ \frac{8R}{3V_{\max}\pi t^2} & \text{(b)} \end{cases}$$

for (a) $0 \leq t \leq \frac{2R}{V_{\max}}$
for (b) $t \geq \frac{2R}{V_{\max}}$.

In addition, the probability density function of the T_R in a cell in which a connection handoff occurs is given by [9]

$$f_{T_R}(t)_{(\text{for handoff cell})} = \frac{3}{2} f_{T_n}(t).$$

Using this function, the arrival and departure times of a user in a cell can be estimated. Such an estimate can be based on some function of the average residence time \bar{T}_R and its standard deviation. Accordingly, the mobility profile M of a user is a set of tuples consisting of the cell id and the estimated residence time in the corresponding cells. The tuples in the set M appear in the order in which the cells are expected to be visited by the user. Table 1 shows an example of a mobility profile M of a user during a multimedia session involving communication of a document viewed from the browsing graph of Fig. 2 while travelling through a set of four cells, predicted by his/her mobility profile. Figure 4a depicts the predicted path of this user, and Fig. 4b illustrates the user's bandwidth profile in four cells.

If the user browses through a different node of Fig. 2 and opens a new document, the bandwidth profile of Fig. 4b may change. A new resource assignment will be required to match the new bandwidth profile for the remaining span of the session while the user continues to travel through the rest of the cells. Such resource reassignment does not have any real-time constraint in the sense that opening a new document can take place momentarily after

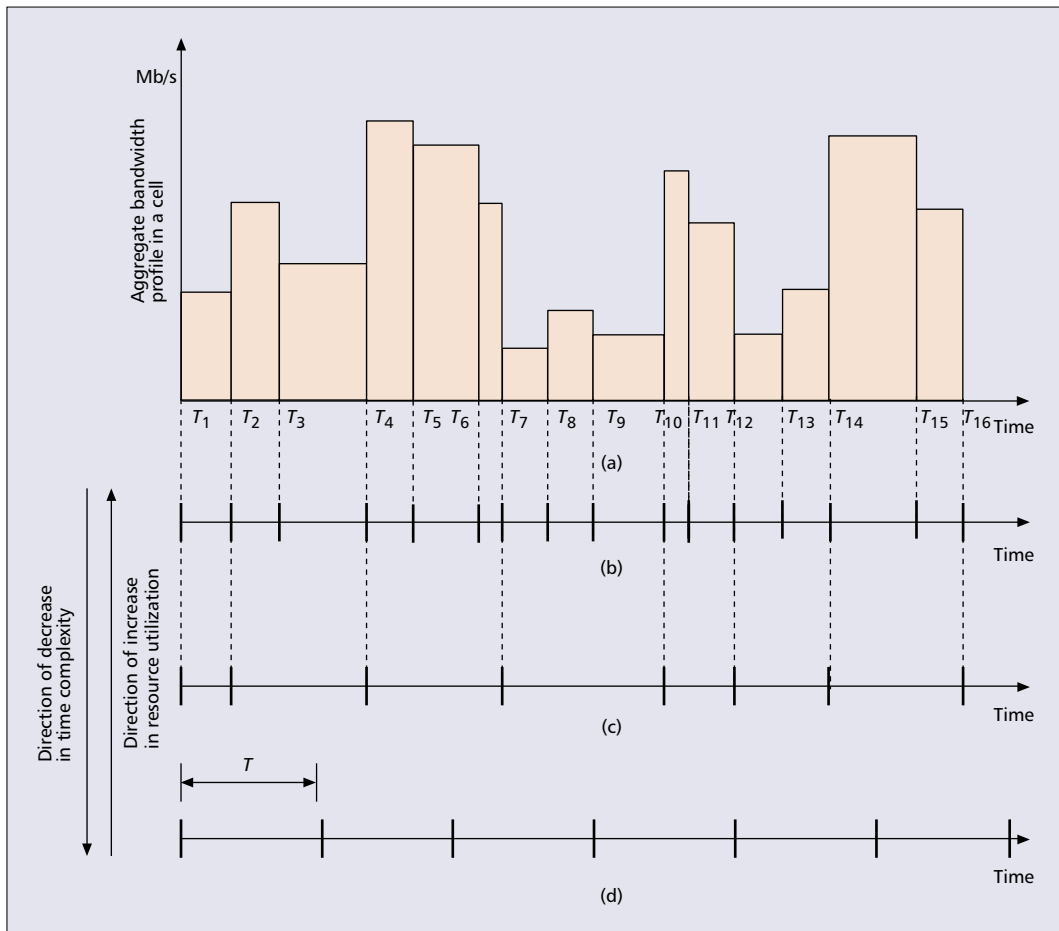
requesting that document. However, the response time in opening this document should be as minimal as possible. The resource allocation request for the new document should be treated with high priority if there are competing fresh requests.

RESOURCE ALLOCATION POLICY

Given the document traffic and mobility profile of a user, the wireless bandwidth resource allocation problem can be formulated as an optimization problem with an objective function comprising QoP parameters. As mentioned earlier, several QoP parameters can be considered for formulating the resource management policy. In this article we take reliability as an example to illustrate such formulation. In addition, we discuss numerous issues that arise in developing a resource management policy and briefly outline approaches to tackle these issues.

The aggregate bandwidth requirement in a cell, depicted in Fig. 5a, is used in our formulation. The bandwidth is aggregated over multiple objects that need to be transmitted for multiple users' sessions. Let $O_1^{(k)}, \dots, O_n^{(k)}$ represent the concurrently transmitted objects with bandwidth requirements $r_1^{(k)}, \dots, r_n^{(k)}$ in a base station of cell k . In addition, the objects $O_1^{(k)}, \dots, O_n^{(k)}$ have reliability requirements $\omega_1^{(k)}, \dots, \omega_n^{(k)}$, respectively, as part of their QoP attributes. It can be noticed from Fig. 5a that the aggregate

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■ **Figure 5.** a) Aggregate bandwidth profile in a cell; time line representation of RADPs using b) a transition-based policy; c) a partial transition-based policy; d) a periodic policy.

The frequency of RADPs directly affects the network performance in terms of resource utilization and computational overhead associated with the execution of NLP-based resource allocation process.

bandwidth requirement changes with time with random transition points T_1, T_2, T_3 , and so on. Such variations occur due to the changing bandwidth profile of concurrent documents. The base station can determine resource requirements at these transition points, which can be called *resource allocation decision points* (RADPs). However, this is an expensive approach with tremendous overhead. At the end of this section, we describe several techniques for selecting RADPs. We first describe how the problem of optimization can be formulated using $\omega_i^{(k)}$ s and provide a mechanism for allocating resources to each object. Such a mechanism needs to be invoked at each RADP.

Let $I^{(k)}$ be the length of interval between two consecutive RADPs i and $i + 1$, whereby the resource allocation mechanism is invoked by the base station in cell k at RADP i for interval $I^{(k)}$. The base station is responsible for assigning appropriate bandwidth capacity for every object in this interval. The length of interval $I^{(k)}$ depends on how frequently resources are allocated and is discussed in detail later in this section. The total bandwidth requirement $\gamma^{(k)}$ in interval $I^{(k)}$ is given by

$$\gamma^{(k)} = \sum_{i=1}^n r_i^{(k)}.$$

If the total bandwidth capacity $C^{(k)}$ in cell k is less than $\gamma^{(k)}$, then at least $(\gamma^{(k)} - C^{(k)}) \cdot |I^{(k)}|$ amount of information in concurrent objects need to be dropped during interval $I^{(k)}$. Let $\theta_i^{(k)}$ denote the dropping ratio of the object $O_i^{(k)}$.

$$\theta_i^{(k)} = \frac{\text{number of SIUs dropped in } O_i^{(k)}}{\text{total number of SIUs in } O_i^{(k)}}$$

A fair channel allocation policy requires that if transmission needs to be degraded, degradation should be uniformly spread across all objects being transmitted concurrently. The problem of uniformly spreading data degradation in interval $I^{(k)}$ can be represented as the following nonlinear programming (NLP) problem:

$$\text{Minimize} \quad \sum_{k \in \mathcal{M}} \left(\sum_{i < j} \left(\theta_i^{(k)} - \theta_j^{(k)} \right)^2 \delta(I^{(k)}) \right) \quad (I)$$

$$\text{Subject to} \quad \left(\sum_{i=1}^n \theta_i^{(k)} |O_i^{(k)}| - (\gamma^{(k)} - C^{(k)}) \right) \delta(I^{(k)}) = 0 \quad (II)$$

$$0 \leq \theta_i^{(k)} \leq 1 - \omega_i^{(k)}, \quad \text{for } i = 1, \dots, n \quad (III)$$

$$\delta(I^{(k)}) = \begin{cases} 1, & \text{if } I^{(k)} \cap [T_d^{(k-1)}, T_d^{(k)}] \neq \emptyset \\ 0, & \text{otherwise.} \end{cases} \quad (III)$$

where $[T_d^{(k-1)}, T_d^{(k)}]$ are the interval points associated with residence time T_R in cell k of the mobile user for which the above bandwidth assignment procedure has been invoked.

Constraints (I) and (II) in the above NLP specify that data degradation should be spread

across the objects in accordance with their reliability requirements. Constraint (III) states that resources for a given mobile user are only allocated in cell k for time interval $I^{(k)}$, provided this interval overlaps with the user's expected residence time T_R in cell k .

The solution to the above NLP may not be feasible, which implies that the reliability requirement cannot be met with the given channel bandwidth capacity. In that case, one possible option for the base station is to override the specified reliabilities. A binary search in an appropriate subinterval of $[0,1]$ could determine the maximum reliability the base station can deliver. Once the largest value of ω that makes the constraints feasible at each switch is determined, the values of the ω_i s are replaced by ω , and the NLP is solved with the newly assigned reliability requirements. Although the above formulation uses a reliability parameter, the formulation is general enough to incorporate other QoP parameters such as resolution, jitter delay, and synchronization.

Selecting RADPs — As mentioned in the previous section, the time markers at which the base station uses the NLP-based resource allocation procedure are the RADPs. The frequency of RADPs directly affects the network performance in terms of resource utilization and computational overhead associated with the execution of the NLP-based resource allocation process. Using RADPs at every transition point of Fig. 5a can result in high computational overhead associated with the execution of the NLP-based resource allocation procedure. In the following, we briefly describe three approaches for selecting RADPs.

Transition-Based RADP Policy — In this policy, every transition of Fig. 5a represents an RADP. These transition points are the union of all the transition points of OCPNs representing documents that are concurrently being communicated in cell k . This policy achieves high resource utilization by allocating the resources at each transition point in the bandwidth profiles of all the documents. However, in a heavily loaded environment, there can be a large number of transition points. Executing the computationally intensive NLP-based capacity assignment procedure at these transition points increases the overall time complexity.

Partial Transition-Based RADP Policy — One way to reduce the computational overhead associated with the transition-based RADP policy is to invoke the NLP-based resource allocation procedure only at those transition points that correspond to a significant change in the bandwidth profile of a document. In other words, the base station executes the NLP-based resource allocation mechanism only if the difference in bandwidth requirements exceeds a certain threshold value Δ . Alternatively, the multimedia document server can quantize the original bandwidth profile of a document with a step size of Δ . As a result, a subset of transition points corresponding to the modified bandwidth profile is chosen. This approach leads to a fewer number

of RADPs, as shown in Fig. 5c. The approach, however, may decrease the resource utilization or degrade the multimedia data quality due to the discrepancy between the actual and quantized bandwidth profiles. To compensate for such degradation, data buffers can be employed at the base stations and in mobile devices.

Periodic RADP Policy — In this scheme, resources are allocated periodically by the base station. Figure 5d depicts RADPs for the periodic policy. Note that the RADPs resulting from this policy may not correspond to the actual transition points. Two design issues need to be addressed in this scheme. First, we need to select an appropriate value for period T , as it affects the computation overhead associated with the NLP-based policy. Second, within T a document profile must have a single value, even if there exist several transitions in the actual document bandwidth profile within that period T . Effective or average capacity approximation can be used to represent the bandwidth requirement of the users in the time interval T [10]. As stated earlier, a single scalar value cannot characterize document-level variations. However, if interval T is small, the mismatch between the actual bandwidth requirement and the approximated bandwidth is expected to be small. Similar to the transition-based policy, this scheme also requires data prefetching to compensate for the rate mismatch.

Several variations of the above mentioned policies can be designed. There exists a trade-off between the computational overhead in solving the NLP problem and possible degradation of QoP as well as utilization of bandwidth resources.

CONCLUSION

In this article we address the issue of managing wireless resources to support Web-based multimedia document services. There is a growing need to support such multimedia services. The resource management problem has been formulated as an optimization problem based on some QoP parameters. Due to the dynamic nature of bandwidth requirements and mobility of users, several resource allocation policies can be developed. There exists a trade-off between the computation overhead associated with the scheduling mechanism and possible degradation of QoP as well as utilization of resources.

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