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Exploiting Information Theory for Adaptive Mobility and Resource Management in Future Cellular Networks

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Abstract

We utilize tools from information theory to develop adaptive algorithms for two key problems in cellular networks: location tracking and resource management. The use of information theory is motivated by the fundamental observation that overheads in many aspects of mobile computing can be traced to the randomness or uncertainty in an individual user's movement behavior. We present a model-independent information-theoretic approach for estimating and managing this uncertainty, and relate it to the entropy or information content of the user's movement process. Information-theoretic mobility management algorithms are very simple, yet reduce overhead by ~80 percent in simulated scenarios by optimally adapting to each individual's movement. These algorithms also allow for flexible tradeoff between location update and paging costs. Simulation results demonstrate how an information-theory-motivated resource provisioning strategy can meet QoS bounds with very small wastage of resources, thus dramatically reducing the overall blocking rate.

Introduction

Packet-based wireless cellular networks are revolutionizing many aspects of ubiquitous mobile computing. In particular, we can observe the following three consequences of the gradual adoption of an IP-based common access infrastructure:

Multiple access technologies are becoming part of a common wireless infrastructure. Service providers have already begun to integrate services over a combination of wide-area cellular access, using standards such as Universal Mobile Telecommunications System (UMTS) and wideband code-division multiple access (WCDMA), and wireless LANs (using 802.11 and Bluetooth technologies). Similarly, mobile devices are also increasingly equipped with multiple interfaces (e.g., Nokia D211 with General Packet Radio Service, GPRS, and 802.11), allowing a single mobile node to concurrently utilize multiple access technologies.

The range of mobile devices utilizing the wireless access infrastructure is becoming very diverse. The packet-based infrastructure will be used by wearable computing devices (e.g., WatchPads), laptop computers, cellular phones, and even automobiles, all of which vary significantly in their processing, memory, and battery capacities.

The set of mobile computing and communications applications is becoming more heterogeneous. Increasingly, applications as diverse as voice over IP (VoIP), broadband video, instant messaging, and Web access are being delivered over a common IP-based wireless network. Each group of applications has its own set of tolerable bounds on performance metrics, such as packet loss, communication latency, and handoff delay.

Designing a common infrastructure that satisfactorily deals with the heterogeneity in all these three axes remains a very challenging problem. Most networks to date have been engineered for specific user or application profiles. For example, the wireless PCS network has been optimized principally for relatively low-bandwidth voice communication, while wireless LANs were primarily designed for data-centric bursty applications. Accordingly, features such as low-latency handoffs and paging are present in cellular networks but absent in WLANs. To accommodate increasing device and application diversity, the infrastructure must now be *adaptive*: capable of tuning its functional behavior to the specific characteristics associated with a particular device, user, or application. In this article we focus on adaptation mechanisms related to two specific cellular network functions:

Mobility management: We shall discuss smart techniques for determining the current location of a mobile node (MN). In particular, we shall define technology-independent algorithms that not only optimize the signaling overhead associated with location tracking, but also allow this overhead to be apportioned between the MN and the base stations in different ratios.

Resource management: We shall explain the problem of provisioning resources over the set of candidate paths of an MN. Specifically, we shall introduce algorithms that enable us to compute a relatively small set of *most likely* paths, such that the MN is probabilistically almost certain to traverse one of the paths of this chosen set. This computation can significantly reduce the burden of overprovisioning and thus increase available cellular capacity.

In contrast to alternative techniques for adaptive mobility and resource management, our approach is based on the network's ability *to observe and learn from* the MN's true movement history. Our work is motivated by the observation that *all MNs and users exhibit some degree of repeatability or predictability* in their movement patterns. Of course, the degree of predictability of different users or devices may be very different, especially with regard to movement or application usage. For example, John's movement pattern may perhaps be significantly similar for each weekday, and is defined by his commuting route from home to office. Similarly, while Mary's calling pattern may be very unpredictable during the weekends, John's calling behavior may be less random. In particular, our innovation lies in the use of tools and techniques from information and coding theory to develop *smart predictive techniques* that achieve provably close to optimal performance.

The rest of this article is organized as follows. We provide the motivation behind the development of the information-theoretic framework for mobility and resource management. The predictive optimal location management (update and paging) scheme is discussed. Subsequently, a new optimal trade-off between update and paging is developed. We highlight the new location-aware resource management framework to support real-time applications over cellular networks. Finally, we conclude the article with pointers to future research.

Why Use Information-Theory-Based Approaches?

While information theory and related concepts such as entropy coding and channel coding have been used extensively in digital communication and storage [1], their use in mobile computing problems has been very limited. Our use of information theory is motivated by the fundamental observation that *the overheads associated with many aspects of mobile computing* (e.g., the signaling overhead in location tracking) *arise from some form of uncertainty or randomness*. In general, the greater the randomness associated with an MN, the higher the resulting overhead. For example, the overheads associated with location management schemes in the current PCS architecture are fundamentally a product of the uncertainty in an MN's location (or movement pattern) [2]. Clearly, if the movement trajectory of an MN is completely deterministic at all instants of time (and available offline to the network), there would be absolutely no location-tracking overhead or waste of provisioned resources. Information theory is the mathematical framework within which uncertainty is expressed, quantified, and managed. Accordingly, it serves as a natural vehicle for investigating the fundamental behavior of mobile computing protocols, especially those related to the management of uncertainty. In this article we concentrate on a few information-theoretic concepts and illustrate their role in the design of associated mobility and resource management protocols. Perhaps the most fundamental concept in information theory is Shannon's definition of entropy, which expresses the average uncertainty associated with the outcome of any random process or variable. Mathematically, for a random variable X, where X takes values in a set $\chi = \{x_0, x_1, \ldots, x_{|\chi|}\}$ (with $|\chi|$ elements) with probability $p[x_0]$, $p[x_1]$, …, $p[x_{|\chi|}]$, respectively, the entropy $H(X)$ is defined (in bits) as

$$H(X) = -\sum_{x \in \chi} p[x] \log_2 p[x]. \quad (1)$$

$H(X)$ provides a quantification of the uncertainty associated with a random process: the more predictable the outcome of a random variable, the lower its entropy. By Shannon's source coding theorem, *no system can accurately convey the outcome of a random sequence to a receiver at a cost lower than its entropy* H(X) *per symbol*. Accordingly, entropy also provides a theoretical lower bound on the efficiency of a lossless communication process.

Rate-distortion theory is the logical generalization of Shannon's coding theorem. While Shannon's source coding theorem proves that lossless communication is impossible if the transmission rate is lower than the entropy, it does not address the possibility of *lossy* communication. In general, a distortion measure D quantifies the degree of inaccuracy between the sequence that actually occurs and the one that is reported to the receiver. The higher the value of D, the greater the inaccuracy of the reported sequence. The rate distortion function $R(D)$ then indicates the lower bound on the *minimum rate (bits per symbol) needed to achieve a distortion bound D*. In other words, $R(D)$ indicates the trade-off between the fidelity of the reported information and the overhead of the reporting process, and is a function of the underlying entropy (randomness) of the source. Clearly, $R(D)$ is a decreasing function of D, with $R(0) = H(X)$ (lossless transmission is lower bounded by the entropy rate).

Closely tied to the notion of entropy is the asymptotic equipartition property (AEP), which loosely states, that for an n-length sequence of the random variable X, most of the probability mass is contained in $\sim 2^{nH(X)}$ unique sequences, each of which has an individual probability of $\sim 2^{-nH(X)}$, especially for large values of n. Thus, while a total of $|\chi|^n$ different n-length sequences of X are possible, only a much smaller set of sequences is plausible or likely. This smaller set of typical sequences is called the typical set. The AEP property is particularly insightful since it relates the question of the number of alternative outcomes that need to be considered, to ensure a probabilistic coverage of the entire sample space, to the underlying entropy. Clearly, the smaller the entropy $H(X)$, the smaller the associated size of the typical set.

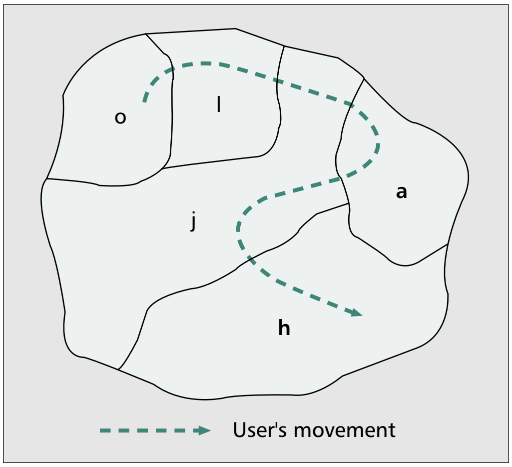


Figure 1. *Symbolic representation of user mobility.*

As mentioned earlier, the problems of both mobility and resource management are tied to the randomness in an individual MN's movement. If we view the MN's movement sequence as the outcome (sample path) of an underlying random process, the corresponding signaling overhead should be a function of the entropy of this random process, with more predictable (lower entropy) movement patterns generating lower overhead. Moreover, information-theoretic bounds are model-independent. Almost all current schemes of mobility or resource management are optimized for specific statistical patterns; for example, dead-reckoning [3] is a strategy best suited when the MN moves mostly in straight-line segments. In contrast, by using practical algorithms that achieve performance close to the entropy or rate distortion bound, we can develop truly universal mobility management protocols (i.e., those that adapt their behavior to all statistical models of movement). The universality of our protocols is especially valuable for heterogeneous networking environments, where no single model of movement or usage applies to all users, applications, or devices.

An Information-Theoretic Approach to Optimal Location Tracking

Location tracking involves two fundamentally distinct operations: *location update*, whereby the MN proactively informs the network of its location, and *paging*, whereby the network searches for the MN within a set of designated cells. This problem can be viewed as the exchange of an MN's location information between itself and the network, since it is this exchange that enables the network to correctly determine the MN's current location. In certain situations, the network also needs to predict the MN's location (e.g., in paging, the network must determine the MN's location since its last update), using, at best, the entire prior movement history of the MN. The ultimate goal of a lossless mobility management scheme is thus to reduce the cost of communicating the MN's movement to the network to as close to the entropy bound as possible.

An information-theoretic approach to location management thus views the MN's movement as a stochastic sequence, and applies appropriate source-coding techniques to communicate this entire sequence at the minimal possible rate. This approach is very different from threshold-based techniques, such as distance-, time-, or movement-based, presented earlier (e.g., in [4]). LeZi-Update [5] was the first such information-theoretic location update technique, which uses the well-known Lempel-Ziv text compression algorithm [6] to achieve near-optimal location update overheads.

As shown in Fig. 1, the LeZi-Update scheme represents the MN's movement as a string or sequence of symbols, where each symbol corresponds to a cell in which the MN resides. Since there is no universal mobility model, the best approach to conveying this information to the network utilizes *adaptive online coding*, where the coding process starts with no prior assumptions. Instead, it gradually *learns* and *builds* the model from the observed movement sequence. *LZ78* offers precisely this property of model-independent online coding. In this approach, the symbols (cell-ids) are processed in chunks, with a new update generated intermittently to report the entire chunk since the prior update. More precisely, each reported chunk defines a new codeword, and an update is generated only when the new chunk is a unique codeword that has not been encountered previously. Thus, each new chunk consists of a previous codeword suffixed by a single symbol. This allows the new codeword to be efficiently transmitting by simply sending the index of the existing codeword along with the single extra symbol. For example, the input sequence S_1 = "*ajlloojhhaajlloojaajlloojaajll*…," is parsed as distinct substrings (phrases) "*a*, *j*, *l*, *lo*, *o*, *jh*, *h*, *aa*, *jl*, *loo*, *ja*, *aj*, *ll*, *oo*, *jaa*, *jll*, …,." This sequence can then be transmitted as (Λ,*a*), (Λ,*j*), (Λ,*l*), (3,*o*), (Λ,*o*), (2,*h*), (Λ,*h*), (1,*a*), (2,*l*), (4,*o*), (2,*a*), (1,*j*), (3,*l*), (5,0), (11,*a*), (8,*l*), …, where Λ is the null codeword. While the MN transmits this encoded sequence, the network is responsible for decoding and storing the reconstructed original movement pattern. For efficient storage, the decoded information is stored in the form of a trie (Fig. 2), where each new chunk results in the creation of a new leaf node, such that the chunk is defined by the path from the root to the leaf. To capture the relative occurrence of different symbols, each update results in an increment of the symbol frequency for *every prefix of every suffix* of the new chunk.

The Paging Process

While the *LZ–78* algorithm focuses on reducing the location update overhead, a separate paging algorithm locates the MN between successive updates. As is well known, the paging process can be optimized if we can construct a probabilistic map of the likelihood of the MN being in different cells. It has been shown in [7] that in the absence of any delay constraints, the expected paging cost is minimized by paging cells sequentially in descending order of occupancy

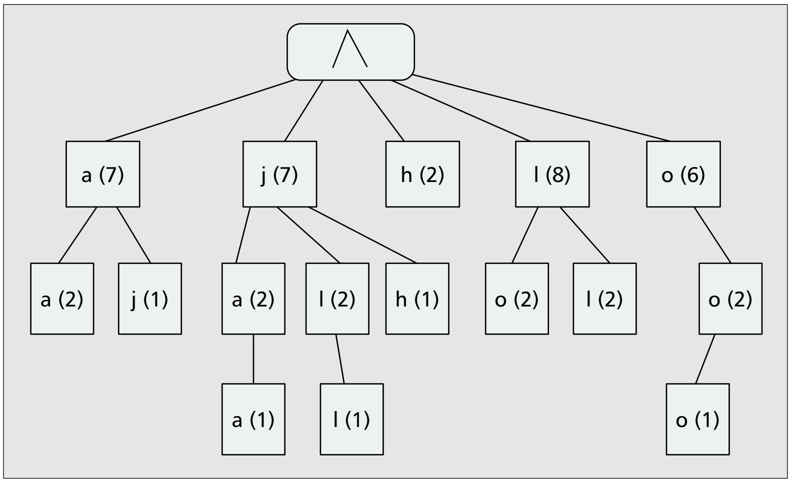


Figure 2. *The trie holding the cells and their frequencies.*

probabilities (more likely cells first). When delay constraints are present, [7] shows how a dynamic programming framework can compute the optimal paging sequence.

The goal of LeZi-Update's paging strategy is to utilize the entire available movement history to compute the optimal residence probabilities of an individual MN. Fortunately, the symbolic movement history of the MN, available in the form of the trie mentioned earlier, allows us to compute these residence probabilities very efficiently. While the details of the probability computation are available in [5], we illustrate the basic process. The first insight is to realize that any movement of the MN since its last report results in a sequence that is already in the trie. Thus, if "*jll*" is the last update message, the network looks for the relative probabilities of different sequences that begin with various suffixes of "*jll*," that is, sequences with prefixes "*ll*," "*l*," and "Λ" (null symbol). The algorithm uses the PPM-style blending technique [8], essentially first computing the conditional probability of each sequence given each suffix of "*jll*," and then computing the unconditional probability by weighing this with the observed likelihood of each such suffix. Once the probability of each sequence is computed, the total residence probability of each individual symbol (cell) in the trie is computed by considering its relative presence in each such sequence. After the cell-level probabilities are computed, the network pages the MN in decreasing order of these probabilities.

This optimal location tracking scheme is extended to multisystem heterogenous cellular networks. The details of this strategy are not in the scope of this article and are found in [9]. We have introduced the concept of *cost entropy* and *session-state information* to capture the different signaling costs and mobile's active/idle state. Centralized, distributed, and heuristic-based location update and paging strategies with different levels of coordination among the subnetworks are formulated. A new near-optimal greedy paging strategy [10] for a heterogeneous network is subsequently proposed.

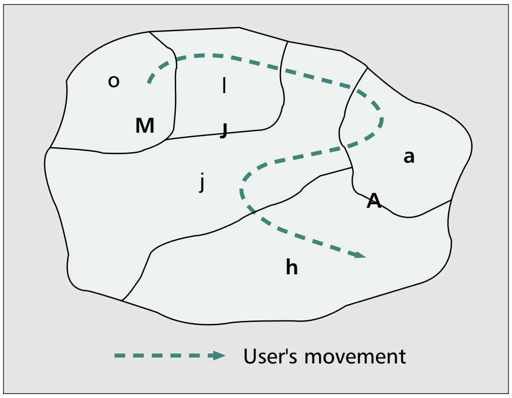
Practical Trade-offs Based on Rate Distortion Theory

While the LeZi-Update strategy achieves near-optimal location management, it does not allow mobile users to arbitrarily trade off between update and paging costs. For example, if two devices, one a WatchPad and the other a laptop, exhibit the same movement pattern, they will have identical update costs, even though the WatchPad is clearly more resource-constrained than the laptop and would possibly like to reduce its update cost even further. Moreover, LeZi-Update does not exploit the registration area (RA)-based location management infrastructure currently deployed in cellular PCS networks. Cellular PCS networks generally cluster a group of cells into RAs such that a mobile's location uncertainty is confined within its last reported RA. We now investigate a framework that permits devices to customize the trade-off between their location update and paging costs, but exploits the existing concept of cellular clusters (RAs).

As the update cost in LeZi-Update is designed to approach the entropy of the MN's movement pattern, it is clear that no further reduction in update cost is feasible without compromising the accuracy of the reported information. This leads us to investigate the use of *lossy quantization* algorithms with the LeZi-Update framework, such that the network does not necessarily receive the mobile's true movement history, but a reasonably close approximation to it. From a theoretical perspective, we are looking for algorithms that result in nonzero distortion D, and are consequently lower-bounded by a rate distortion value $R(D)$ even lower than $H(X)$. Intuitively, we aim to reduce the update cost even further by allowing some loss of information.

We restrict ourselves to two simple variants of LeZi-Update in this article, details of which are available in [11]. The modified protocols are motivated by a fundamental result [12] that *a cascaded combination of scalar quantization and entropy coding usually results in a communication overhead fairly close to the lower bound of rate distortion theory*. In this enhanced framework, the network still receives the update from the MN as a sequence of symbols. Now, however, *each symbol represents an RA* (or group of cells), rather than an individual cell. The MN essentially has quantized its location coordinates, revealing its cell-level location information at the coarser granularity of the RA. Figure 3 shows the organization of the cells shown in Fig. 1 into three different RAs, A, J, and M are consisting of cells (a, h), (j, l), and (o), respectively.

In the first approach, called LeZi-RA, the MN's movement pattern is first quantized into a sequence of RAs on which the *LZ78*-based incremental parsing technique is applied. The new quantized, lossy RA sequence becomes: "*A*, *J*, *J*, *J*, *M*, *M*, *J*, *A*, *A*, *A*, *A*, *J*, *J*, *J*, *M*, *M*, *J*, *A*, *A*, *J*, *J*, *J*, *M*, *M*, *J*, *A*, *A*, *J*, *M*, *J*." The incremental parsing results in "*A*, *J*, *JJ*, *M*, *MJ*, *AA*, *AAJ*, *JJM*, *MJA*, *AJ*, *JJMM*, *JAA*, *AJM*, *J*…." In the second approach, called RA-LeZi, the run length of the quantized



■ **Figure 3.** *Organization of cells into RAs.*

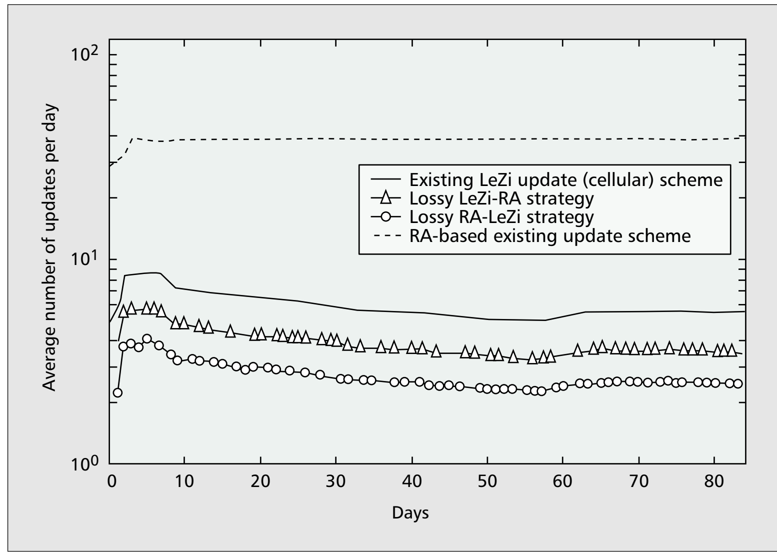
RA sequence is ignored, and a new quantized sequence is generated only when the mobile changes its current RA. Thus, the lossy quantization and its subsequent parsing of the original sequence S1 now result in the sequence "*A*, *J*, *M*, *J*, *A*, *J*, *M*, *J*, *A*, *J*, *M*, *J*, *A*, *J*, *M*" and set of phrases "*A*, *J*, *M*, *JA*, *JM*, *JAJ*, *MJ*, *AJ*, *J*…." The *LZ78*-based LeZi-Update scheme is then applied on these modified RA-level sequences, rather than the original cell-level movement sequence.

At the network end, however, the paging process is identical for both these schemes. The residence probability of every symbol (RA) in the trie is computed as before and *equally distributed* among its constituent cells. The paging strategy then polls the RAs according to their *normalized residence probabilities* (residence probability divided by RA size). With each RA the cells may be paged either simultaneously or sequentially in random order. The increased uncertainty in the paging process arises from the fact that quantization into RA-level information loses the details about the MN's precise movement pattern *within* an RA. Naturally, we can expect the paging costs with these two quantized protocols to be higher than those of LeZi-Update. However, as rate distortion theory shows, the paging costs would be the minimal possible, given the reduced location update costs.

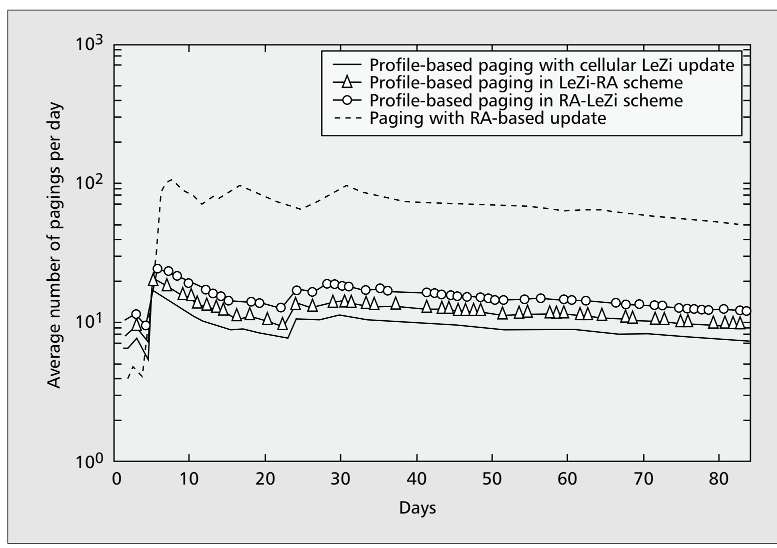
Sample Performance Results

To understand the advantages of the basic LeZi-Update scheme and the two quantized versions, we simulated their performance for a particular user movement pattern. We used different mobility patterns for weekdays and weekends, with normally distributed cell residence time and a Markov-modulated call arrival process with three distinct states (weekday daytimes, weekday evenings, and weekends), each having its own Poisson arrival rate (λ = 0.2, 0.3, 0.5 calls/h) and normally distributed holding times (μ = 10, 20, 30 min, σ = 3, 5, 7 min).

Figure 4 shows that the update cost of such a path-based LeZi Update scheme is only ~14 percent of the currently used RA-based update strategy. The proposed LeZi-RA and RA-LeZi improve the update cost even more, resulting in only ~ 9 percent and ~ 7 percent of update cost of the RA-based update strategy. Figure 5 demonstrates that the profile-based paging associated with LeZi Update results in only ~11 percent paging cost in comparison to the paging associated with the existing RA-based techniques. The improvement in update costs achieved by the LeZi-RA and RA-LeZi schemes comes at the expense of higher paging costs. Figure 5 shows that the paging costs associated with LeZi-RA and RA-LeZi schemes are bounded by only ~1.8 and ~2.3 times that of the optimal profile-based paging cost provided by the optimal paging of LeZi-Update.



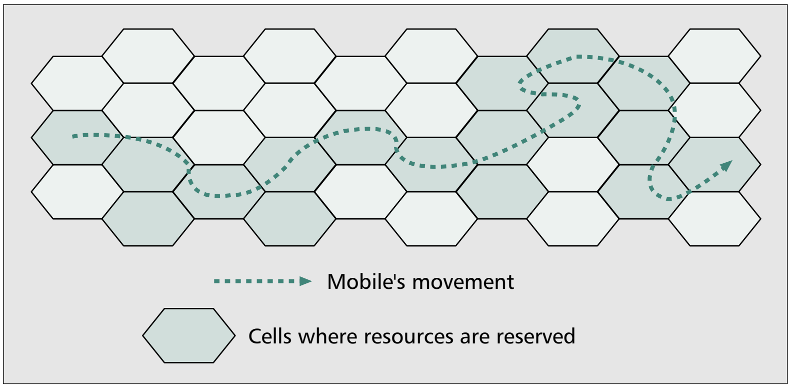
■ **Figure 4.** *A comparison of update costs.*



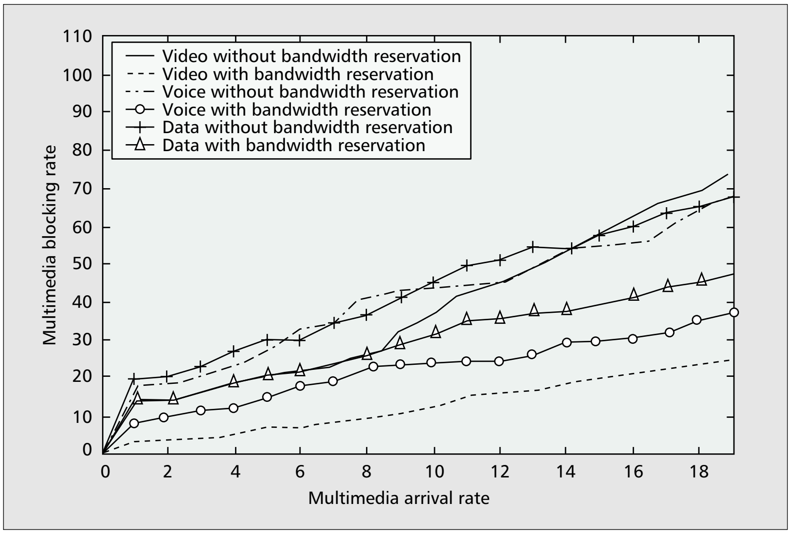
■ **Figure 5.** *A comparison of paging costs.*

Location-Aware Resource Management

To satisfy the QoS guarantees required by a traffic session, the network must reserve resources at cells an MN can potentially visit in the near future so that they are guaranteed to be available if the MN moves there. There is, of course, a trade-off between guaranteeing QoS and wasting provisioned resources. Clearly, to absolutely



■ **Figure 6.** *Resource reservation along a user's typical routes.*



■ **Figure 7.** *Blocking of wireless traffic.*

guarantee that resources are available irrespective of the MN's movement, the network would have to reserve appropriate resources (e.g., session bandwidth) at *all* cells. This would be tremendously wasteful, since the MN would typically never visit most of these cells. Current schemes, such as the shadow cluster approach [13] or LZ-based prediction technique [14] reserve resources only in the entire or selected vicinity of an MN's current location.

By using the notion of typical sets, we can, however, provide greater coverage guarantee, while requiring resource provisioning only along a relatively small set of the user's *most probable routes* (paths) in the near future. Intuitively, we compute the small set of typical routes that reduce not only the location but also the *directional uncertainty* of the MN. From a practical perspective, the approach consists of first determining the empirical entropy $H(X)$ of the MN's movement sequence, and then determining the typical sequences as those whose empirical probability (as observed in the trie stored in the network) is close to the typical probability $2^{-nH(X)}$. Since different sequences will have different lengths n, their inclusion in the typical set is based on how closely their empirical probability approximates that of a typical sequence of identical length. Figure 6 highlights this concept of typical-set-based reservation of wireless bandwidth. For the example presented earlier, the typical set is computed to be routes $\{R^n\} = \{l, ll, loo, jaa, aa\}$. The bandwidth is reserved along each cell in the set of typical sequences in proportion to the residence probability of the user.

To demonstrate the utility of this approach, we simulated the behavior of mobile users with voice, video, and data traffic. The wireless video and data traffic is generated using the International Telecommunication Union's (ITU's) H.264 specifications with 176 × 144 pixel resolution and fluid queues having Weibullian interarrivals with heavy tails. Figure 7 demonstrates that such mobility-aware proactive bandwidth reservation results in almost 50 percent, 65 percent, and 30 percent improvement, respectively, in blocking of wireless voice, video, and data streams during handoff with increasing session arrival rates. This improvement in blocking occurs since the network is now smarter and reserves resources optimally for an MN (i.e., only along its likely paths). Moreover, the protocol is universally adaptive: if an MN has a more random movement pattern, the network will automatically reserve resources over a larger set of paths to reflect the increased uncertainty.

Conclusion

Information theory and related tools provide a rich framework to study and develop protocols for various mobile computing functions. By viewing the MN's movement as a realization of an underlying stochastic sequence, we can use entropy and rate-distortion functions to characterize the fundamental randomness of the movement pattern. We have shown how adaptive online coding techniques can achieve location update overhead close to the entropy or rate-distortion bounds, by essentially adjusting the update algorithm to optimally exploit the underlying patterns in an MN's movement. Similarly, by using the notion of typical sets and sequences, we can see how resources for different traffic sessions of an MN can be reserved along a relatively small number of likely future paths, thereby substantially decreasing the overall blocking probability for all traffic classes.

We believe that information-theoretic insights and tools can significantly improve many aspects of mobile communications. As an example of an open problem in location management, note that our current solutions require the storage of per-MN movement profiles, which may either be too expensive for large mobile populations or generate privacy concerns. In future research, we would like to derive adaptive algorithms that operate on the collective pattern of aggregates of MNs, where the right level of aggregation is also determined via information theory concepts such as relative entropy among multiple MNs. More important, the need for adaptive network behavior permeates other network-layer functions, such as admission control, resource provisioning, QoS allocation, and power control, all of which have to cope with the uncertainty of wireless links and user behavior. Accordingly, information theory will be vital in the development of an *autonomic* wireless network infrastructure, where the network behavior intelligently adapts to changes in physical layer or user behavior.

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