CARP: Context-Aware Resource Provisioning for Multimedia over 4G Wireless Networks

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Abstract. In this paper a context-aware resource provisioning framework is developed for multi-system, heterogeneous 4G wireless networks. The framework envisions that each individual sub-network is fairly independent, and uses Bayesian learning scheme for capturing user's mobility profiles. The concept of Asymptotic Equipartition Property (AEP) helps to predict the most likely path-segments, that the mobile user (MU) is going to follow in near future, with very good accuracy. This helps in proactive resource management along the MU's future paths and locations providing the optimal resource (e.g., bandwidth) reservation. Simulation results on a synthetic wireless traces corroborate this high prediction success and demonstrate sufficient improvement in delay, blocking and throughput of ongoing wireless multimedia sessions.

Keywords: 4G Heterogeneous wireless networks, Bayesian learning, resource management, Information Theory, mobile multimedia, AEP.

1 Introduction

The concept of packet-based, next-generation 4G wireless networks [2] lies in the co-existence of multiple cellular access networks. These individual cellular networks might possess significant differences in topology, coverage area and transmission range. However, by using multiple radio interfaces, future mobile nodes can seamlessly switch between these technologies, thus achieving the ultimate goal of global roaming. The 4G network can thus be conceptually visualized as a collection of multiple independent access *sub-networks*, each of which has its own cellular layout and separate location tracking technique. "Context-awareness" is perhaps the key characteristic of these next-generation wireless networks and associated applications. *Mobility and location information* is the most important "context" in these networks, because the information needed by the vast majority of MUs depend strongly on their current or near future location.

In this paper we have developed a new Context-Aware Resource Provisioning scheme *CARP* across mobile-user's most frequent routes in heterogeneous 4G cellular networks. Operating in *symbolic space*, *CARP* uses Bayesian algorithm to capture the movement profiles of individual MU across such networks. Although, in such systems, there exists a wide number of possible routes from a

particular source to a destination, a MU usually follows his/her most likely paths. A similar analogy, dealing with the *asymptotic equipartition property* (AEP) [11] states that among all the long-range sequences consisting of random variables, there exists a fairly small *typical set* [11] which contains most of the probability mass and controls the average behavior of all such sequences. Using this concept, CARP captures the MU's *typical path segments* and reserves bandwidth along the typical paths. This helps in seamless transmission of ongoing real-time wireless communication with specific Quality of Service (QoS) guarantee. Using a priority-based service classification scheme CARP is also capable of guaranteeing significant improvement in blocking of real-time multimedia sessions.

Section 2 reviews the major existing works in location and resource management in 4G networks. A symbolic domain description of such networks is shown in Section 3. The new concept of capturing MU's frequently used routes is developed in Section 4. An efficient resource reservation and admission control scheme based on this route formation is discussed in Section 5. Simulation results in Section 6 demonstrates the improvement of QoS in ongoing wireless sessions. Finally Section 7 concludes the paper.

2 Related Works: Mobility in 4G Wireless Systems

Given the large body of work on resource management in a single cellular access system (e.g., PCS), we survey only the major contributions related to our context. The guard channel policy [8] and fractional guard channel policy [9] determine the number of guard channels for hand-offs. The shadow cluster scheme [6] estimates future resource requirements in a collection of cells in which a mobile is likely to visit in the future. An efficient scheme for mobility-based predictive admission control is also proposed in [12] for single-system wireless networks.

Some recent work has reported on the problem of location and resource management in a multi-system environment. It is shown in [1] that an integrated location management strategy can significantly outperform an independent operation of each sub-system's location management algorithm. Similarly recent researches have pointed out a significant trend towards seamless inter-networking of wireless LANs and cellular networks [3]. The issues of network selection [10] in heterogeneous wireless networks are also under investigation. The problem of optimal location management [7] in heterogeneous wireless networks is also recently pointed out. However, the problem of resource reservation and management for guaranteed QoS in a generic multi-system environment is yet to be effectively addressed. This motivates the development of *CARP*.

3 Symbolic Representation of 4G Wireless Systems

Figure 1 shows an example of an *integrated 4G wireless network*, comprising a collection of satellite, PCS and campus area (IEEE 802.11 WLAN and Bluetooth) based independent sub-networks. Clearly, the coverage area of each individual sub-system can be discontinuous. Accordingly, the set of sub-networks that can

Fig. 1. A Multi-System Heterogeneous Wireless Network

be accessed concurrently by a mobile node is not constant but a function of its current location. Let, the 4G network consists of N sub-networks, where each sub-network is a collection of (either partitioned or overlapping) cells, such that C_i^j represents the j^{th} cell in the i^{th} sub-network. If the mobile node is currently out of range of sub-network S_i , its location vector includes the cell C_i^ϕ .

The movement pattern of the mobile node (MN) can then be represented as a N -dimension random vector $\bar{X}$, where the i^{th} element of the vector corresponds to the current cell of sub-network S_i . For instance, if $\bar{X}(2) = 4$, the MN is currently located in the 4^{th} cell of sub-network S_2 . Characterizing the mobility as a probabilistic sequence suggests that it can be defined as a stochastic, vector-valued process $\chi = \{\bar{X}_n\}$, where the “...” imply that the corresponding random variable can take any possible value within its range.

4 Context-Awareness in Heterogenous Wireless Networks

The MU’s location uncertainty in heterogeneous wireless networks leads to uncertainty in the resources allocation and reservation policies. Once the location is managed properly, only then the network will be smart enough to reserve suitable wireless bandwidth. While the existing shadow cluster [6] approach provides the idea to preserve resources along the mobile’s surrounding cells, it fails to give any generalized way to estimate these shadow clusters, and only assumes either some definite knowledge of user mobility or totally random users. The novelty of *CARP* lies in the fact that it not only captures the MU’s locations, but also accumulates and predicts the user’s *typical* routes. Thus, effectively *CARP* extends the concept of shadow cluster into heterogenous wireless networks to form a more smart resource management scheme.

4.1 Probabilistic Estimation of User-Mobility

CARP uses an online *Bayesian Aggregation* technique [4] to make the system knowledgeable enough about the MU’s mobility profiles. Figure 2 provides a pseudo-code of our mobility prediction scheme. Each cell-vector $\bar{X}_i$ in the heterogenous wireless system is assigned to a weight w_i . Initially, all the weights are

Probabilistic Mobility Prediction

1. initialize $m := 1$; assign weight $w_i := 1/n$ to each instant $\bar{X}_i$;
3. repeat steps below until $(X_p - X_a \leq \varepsilon)$;
4. predict the next cell-vector (location) $\bar{X}_p := \sum_{i=1}^n \frac{w_i \times \bar{X}_i}{w_i}$;
5. continue it's own movement; 6. Capture the actual location $\bar{X}_a$;
7. compute the individual (l_i) and overall (l_o) prediction inaccuracy $l_i = -|\bar{X}_a| \ln |\bar{X}_i| - (1 - |\bar{X}_a|) \ln(1 - |\bar{X}_i|)$ and $l_o = \sum_{i=1}^n l_i$;
8. update the weights as: $w_i^{m+1} = w_i^m e^{-l_i}$;

Fig. 2. Bayesian Algorithm for Capturing User-Mobility

same, i.e., $w_i = 1/n$. The mobile-node now estimates it's own future-location by computing a *weighted measure* of these individual instances of cell-vectors (locations). Formally, the predicted location $\bar{X}_p$ is:

$$\bar{X}_p = \frac{\sum_{i=1}^n w_i \times \bar{X}_i}{\sum_{i=1}^n w_i} \quad (1)$$

The objective of *CARP* is to predict the future location correctly, so that *the system becomes cognizant of user's mobility*. If, $\bar{X}_a$ represents the actual location, the objective is to make the system cognizant enough so that $\bar{X}_p = \bar{X}_a$. The most fair measure of the prediction-inaccuracy (error) associated with this process is *entropic loss* [4]. This *entropic loss* l_i for each location and its cumulative estimate in m iterations l_i^c is given by

$$l_i = -|\bar{X}_a| \ln |\bar{X}_i| - (1 - |\bar{X}_a|) \ln(1 - |\bar{X}_i|), \text{ and } l_i^c = \sum_{i=1}^m l_i \quad (2)$$

At every iteration m , the weights associated with every time-instant T_i are now updated as

$$w_i^{m+1} = w_i^m e^{-l_i}. \quad (3)$$

This procedure is iterated until $\bar{X}_i - \bar{X}_a \leq \varepsilon$, where ε is a predefined precision. The effects of locations far from accuracy are reduced by exponentially decreasing their associated weights. In time the predicted location $\bar{X}_i$ approaches $\bar{X}_a$. The overall expected deviation from the optimality (l_o) is given by:

$$l_o \leq \min_i l_i^c + \ln(m) \quad (4)$$

4.2 Context-Aware Route Collection

A close look into the life-style of a particular MU reveals that he/she typically follows only a small subset of all the paths, which essentially is guided by his life-style in the long run. The concept of *typical set* and *asymptotic equipartition property* (AEP) from information theory helps in obtaining this *small set* of *highly probable* routes maintained by a particular MU.

Definition 1. The type [4] of a vector-sequence $\bar{\mathbf{x}} = \{\bar{x}_1, \bar{x}_2, \dots, \bar{x}_n\}$ is the relative proportion of occurrences of each vector-symbol. Also, the set of all vector-sequences of a particular length and type is referred as the type class.

The essential power of the method of types arises from the fact that the number of types is *always at-most polynomial* [11]. Hence, the crucial point to note here is that, there are polynomial number of types, but exponential number of sequences.

Result 1. If $\bar{\mathcal{V}}_1, \bar{\mathcal{V}}_2, \dots, \bar{\mathcal{V}}_n$ denotes the set of vector-sequences drawn according to a specific distribution, then the probability of the sequence depends on *relative difference* between the type and the original distribution.

Hence, the type classes and the corresponding sequences that are far from the original distribution have exponentially smaller probabilities. This leads to the concept of *typical set*:

Definition 2. For a given $\epsilon > 0$, a typical set T_Q^ϵ of sequences for the distribution Q^n is defined as: $T_Q^\epsilon = \{\bar{\mathbf{v}} : |\text{Type} - \text{Distribution}| < \epsilon\}$.

All we now need is the probabilistic estimation of these typical sequences. Fortunately, this is exactly what the *Shannon-McMillan-Brieman* theorem [4,11] provides. According to this theorem, if $H(\chi)$ is the entropy of finite-valued stochastic ergodic process χ , then

$$-\frac{1}{n} \lg [p(\bar{V}_0, \bar{V}_1, \dots, \bar{V}_{n-1})] \rightarrow H(\chi) \quad (5)$$

Equation 5 provides the basis of *asymptotic equipartition property* (AEP) [11] for any stationary, ergodic, stochastic process.

Result 2. AEP states that for a fixed $\epsilon > 0$, as $n \rightarrow \infty$, $\Pr\{\chi \in T_Q^\epsilon\} \rightarrow 1$.

This is basically similar to the *weak law of large numbers* [4] for ergodic, stochastic sequences, assuring that asymptotically almost all the probability mass of $\mathcal{V}$ is concentrated in the *typical set*. It encompasses the mobile user's most likely paths and determines the *average nature* of the large route-sequences.

5 Advanced Resource Provisioning

Resource reservation and admission control for multimedia services is a challenging research topic in the field of current and future generation wireless networks. The novelty of our approach lies in designing the bandwidth reservation scheme along the MU's typical (most probable) set of routes to ensure strict guarantee of QoS parameters like delay, throughput and blocking of real-time wireless applications; which had been missing from literature. The wireless audio-video applications are now capable of following the MU along his/her typical routes. Thus, the MU will be able to listen the news and watch a streaming video as he/she moves from one location to another. An estimation of reserved and free bandwidth in any heterogeneous cell $\bar{z}$ is determined by:

$$B_{res}(\bar{z}, m) = Pr[\bar{z}] \times B_m = \sum_{\bar{X}^n \in T_e^Q} \left[Pr[\bar{X}^n] \times \frac{f(\bar{z})}{|\bar{X}^n|} \right] \times B_m, \quad (6)$$

$$B_{free}(\bar{z}, m) = B_{tot} - B_{res}(\bar{z}, m) \quad (7)$$

where, $f(\bar{z})$ represents frequency of occurrence of $\bar{z}$, B_{tot} , B_m , B_{resv} and B_{free} are respectively the total bandwidth requirement of the mobile m , bandwidth requirement at $\bar{z}$, bandwidth reserved at $\bar{z}$ and free bandwidth at $\bar{z}$.

On arrival of a particular media packet in any $\bar{z}$, the bandwidth availability in that zone is checked for admission of the real-time video and voice stream. The unavailability of bandwidth leads to blocking of the media stream. On the other hand, if the bandwidth is available, the availability is checked only along the typical routes of the MU. The admission control of the multimedia packets is determined by the following condition:

$$\sum_{\bar{z} \in \mathcal{V}^n} Pr[\bar{z}] \times \beta(\bar{z}, B_m) \geq \tau \sum_{\bar{z} \in \mathcal{V}^n} Pr[\bar{z}], \quad (8)$$

$$\beta(\bar{z}, B_m) = \begin{cases} 1, & B_{free}(\bar{z}) \geq B_m \\ \frac{B_{free}(\bar{z}, m)}{B_m}, & \text{otherwise} \end{cases} \quad (9)$$

where τ is the admission threshold. Clearly, τ varies for voice, video and data packets. The data packets are given lower priority, and are admitted only if sufficient bandwidth is left (according to equations (6)–(9)) after admitting the real-time voice and video traffic.

6 Simulation Results

We have developed an object-oriented, discrete-event simulation environment for supporting MU's movements, associated prediction of typical routes and resource management for supporting location-aware multimedia services. The wireless voice services is modelled with exponentially distributed 'on' and 'off' periods (mean lengths 0.6 sec and 0.8 sec respectively). We have taken fluid queues having Weibullian inter-arrivals with heavy tails. The video sequences, are assumed to be encoded with ITU's (International Telecommunication Unit) H.264 [5] specifications with 176×144 pixel resolution and 7–30 frames/sec.

CARP reserves the highest bandwidth for ongoing voice (40%–45%-high priority) and the lowest for data traffic (10%–15%-low priority) along the MU's typical routes. Figure 3 demonstrates that the such a mobility-aware, proactive bandwidth reservation results in almost 50%, 65% and 30% improvements respectively, in blocking of wireless voice, video and data streams, with increasing session arrival rates. In order to investigate into the mutual effect of the real-time voice and video streams over the other, we have looked into the throughput of voice and video traffic. Figure 4 shows that the with increasing session arrival rate the throughput of voice and video traffic lies around 65%–85% of the actual transmission data rate. Thus, we can conclude that such a location-aware

Fig. 3. Gain in Blocking of Mobile Multimedia

Fig. 4. Throughput of Voice and Video Traffic

Fig. 5. Mutual Effects of Voice and Data Traffic

bandwidth reservation scheme has the potential for providing steady throughput of multimedia streams. Another point of concern is the mutual effects of traffic over the delay experienced by the MU in receiving the multimedia streams, while

moving from one location to the another along the typical routes. Figure 5 shows that using this delay can be kept quite low for voice (≈ 600 msec) services.

7 Conclusions

In this paper we have looked into the advanced resource reservation scheme for location-aware multimedia in heterogenous wireless networks. The developed system is quite cognizant about the MU's daily movement patterns and is capable of performing advanced reservation of wireless bandwidth along the MUs typical routes. This proposed framework aids in development of location-oriented multimedia with specific QoS (delay and throughput) guarantee, reduced blocking and seamless transmission along the MU's typical routes.

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