Storage-Aware Routing Protocol for the MobilityFirst Network Architecture

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***Abstract*—This paper presents an overview of the storage-aware routing protocol proposed for the *MobilityFirst* network architecture being developed as a part of the NSF Future Internet Architecture (FIA) project. The storage-aware routing method described here is a generalized form of delay-tolerant network (DTN) intended to work seamlessly across both wired and wireless networks. An adaptive storage-aware routing algorithm (ASTAR) which uses a combination of short and long-term path quality metrics along with available buffer storage to make store vs. forward decisions at routers is described. Selected experimental trace-driven validation results are given for an example hybrid network incorporating wired backbones and heterogeneous radio access technologies. The proposed storage-aware routing algorithm under consideration is shown to provide significant capacity and performance gains for the mobile/wireless usage scenarios considered. It is further demonstrated that the ASTAR adaptation algorithm provides a unified mechanism for adjusting store/forward decisions in response to variations in path quality, available router storage and traffic levels, achieving up to 20% capacity improvement over baseline non-adaptive schemes.**

***Index Terms*—Future Internet Architecture, storage-aware routing, adaptive routing, delay tolerant networks, *MobilityFirst*, ASTAR.**

I. Introduction

This paper introduces the adaptive storage-aware routing protocol which has been proposed for use in the *MobilityFirst* future Internet architecture project currently in progress [1]. The *MobilityFirst* architecture is one of several ongoing collaborative research efforts funded under the US National Science Foundation's FIA program aimed at design, prototyping and evaluation of a clean-slate protocol stack for the future Internet [1]. Each FIA project has its own unique emphasis. The *MobilityFirst* project led by Rutgers University is motivated by the fast-growing numbers of mobile end-points on the Internet, which are expected to significantly outnumber fixed hosts on the Internet by 2015 [2]. The *MobilityFirst* protocol architecture recognizes mobile computing on wireless devices as the predominant mode of Internet usage in the future, and thus includes design features intended to deal directly with the problems of mobility and radio access.

One of the key components of the proposed *MobilityFirst* architecture is storage-aware routing which utilizes routers with in-network file memory to significantly improve end-to-end performance in the presence of fluctuating wireless link bandwidth and disconnections due to mobility [3], [4]. The storage-aware routing methods under consideration for the new architecture may be thought of as a generalization of delay tolerant networks (DTN) which have been designed to deal with usage scenarios involving high mobility and frequent disconnections. In this paper, we introduce a specific adaptive storage-aware routing protocol (called ASTAR) which works well over hybrid wired and wireless networks by combining the properties of conventional wired network routing with the disruption tolerance of DTN protocols. Preliminary validation results will be given for the proposed ASTAR protocol running on a hybrid network incorporating a mix of wired and wireless link technologies, demonstrating the potential for significant performance gains in anticipated mobile service scenarios.

The contributions of this paper can be summarized as follows:

1) Overview of the *MobilityFirst* network architecture and the implications for the routing required in anticipated mobile/wireless usage scenarios.
2) Discussion of enhancements to the storage-aware routing protocol [5], [6] proposed earlier in conjunction with the Cache and Forward (CNF) [3] networks for making it suitable for use in the *MobilityFirst* protocol stack.
3) Description of the adaptive storage routing (ASTAR) algorithm which takes into account variations in link quality, disconnection and available storage at routers.
4) Sample validation results based on trace-driven modeling are used to demonstrate the performance gains with adaptive storage-aware routing.

Paper Organization: The rest of the paper is organized as follows. Section II presents the related work. Section III outlines the *MobilityFirst* architecture and identifies storage-aware routing protocol requirements within the protocol stack. Section IV discusses the adaptive storage-aware routing (ASTAR) protocol under consideration. Section V provides preliminary results based from a trace driven model and finally, Section VI presents conclusions and future directions.

II. Related work

Anticipated paradigm shifts in internet usage have motivated a number of national research programs aimed at clean-slate architecture - these include the NSF future Internet architecture (FIA) [1], future Internet design (FIND) [7] and GENI [8] in the US, FP7 Future Networks [9] and FIRE [10] in Europe and NGN (New Generation Networks) in Japan [11]. FIA, FIND and FP7 focuses on a re-thinking of the basic design principles of the Internet, while GENI and FIRE aim to provide the large-scale experimental networking infrastructure necessary for validation of new protocol ideas. There are a number of architectural proposals that have been published over the past few years. These include Content Centric Networking (CCN) [12] which aims to deliver content efficiently by incorporating content-aware routing techniques at the core of the network. Other proposals include the Accountable Internet Protocol (AIP) [13] which integrates accountability with routable internet addresses by including self-certifying public key addresses. Another example of a new architecture is Hierarchical Architecture for Internet Routing (HAIR) [14] which proposes a hybrid between name-based and address-based routing to deal with requirements such as mobility and multi-homing. The *MobilityFirst* architecture discussed in this paper has some similarities to architectures like AIP, HAIR and CCN, but is distinguished by the focus on mobility and wireless access leading to new mechanisms for naming, addressing and routing.

The routing component of *MobilityFirst* which is the main focus of this work uses storage-aware routing methods to achieve good performance in presence of varying wireless access link quality and/or disconnections due to mobility. Current DTN routing protocols like PRoPHET [15], MaxProp [16] and RAPID [17] typically use epidemic routing protocols to deal with extreme mobility environments and are thus not suitable for more mainstream Internet access scenarios. The basic storage aware routing protocol [5], [6], [18] in CNF networks [3] is intended to operate over a range of wireless access scenarios, and is considered as a starting point for the proposed ASTAR routing algorithm described in this paper. This work goes beyond earlier storage-aware routing papers by introducing a general adaptation algorithm which takes into account factors such as link quality/rate, disconnections and available storage.

III. Background: *MobilityFirst* & Storage Aware Routing

A. The MobilityFirst *Architecture*

The proposed *MobilityFirst* architecture is based on the following set of high-level design requirements: (1) **Mobility as the norm:** Seamless host and network mobility at scale; multi-provider mobile network access; heterogeneous wireless technologies. (2) **Robustness:** with respect to intrinsic properties of wireless medium (disconnection, varying bandwidth, high error rates, scarce spectrum). (3) **Trustworthiness:** Enhanced security for mobile networks and wired infrastructure (strong authentication, enhanced trust models, privacy, DDoS resistance, secure routing). (4) **Usability:** Architectural support for context-aware pervasive mobile services; evolvable core network services; network manageability; economic viability, regulability and universal access.

The *MobilityFirst* network architecture resulting from these considerations is conceptualized in Figure 1. Because the design is aimed at supporting billions of mobile users, a central feature is a fast global naming service that dynamically maps device names to network addresses while providing strong

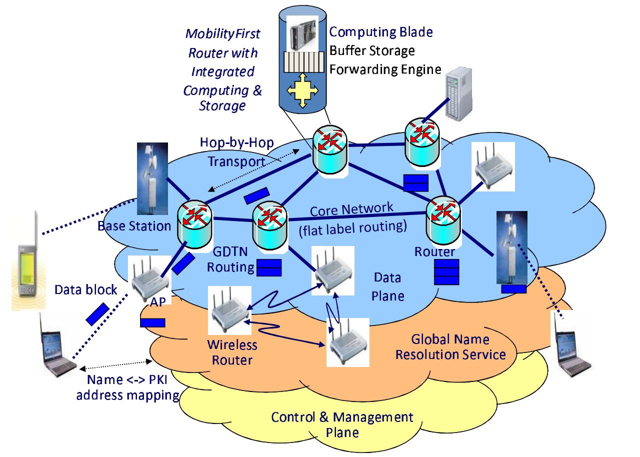

Fig. 1. High level overview of the components of the *MobilityFirst* architecture.

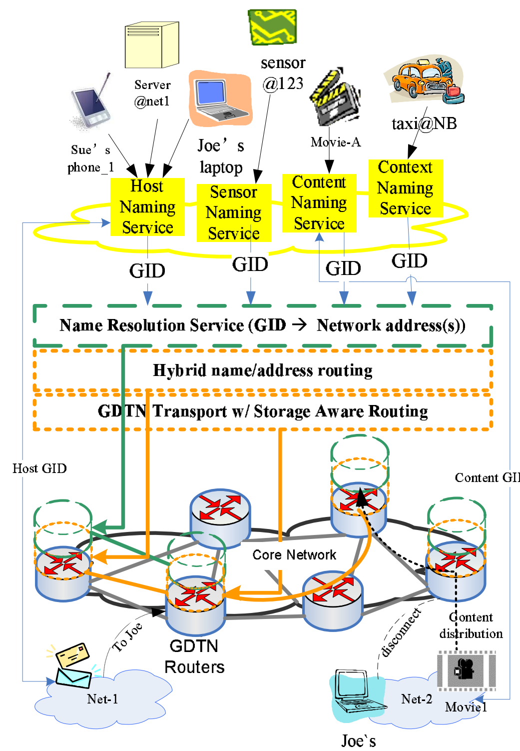

Fig. 2. Overview of the *MobilityFirst* protocol stack.

authentication. This allows end-users to have a permanent name and receive dynamic addresses as they move from one attachment point to another, or reconnect after a period of disconnection. For strong security, we use self-certifying public key network names and associated mechanisms that avoid a single root of trust (such as ICANN [19]) in the network. Data transport is based on the concept of a class of routers with in-network storage and connectionless transport of application-level blocks over path segments between such storage-capable routers of as the norm. Coupled with storage-aware or generalized delay-tolerant network (GDTN) routing in the access network, this provides significant robustness in presence of link/network disconnections, as well as a foundation for adding programmable computing services such as enhanced security or content/context-sensitive delivery. Other features include a cleanly separated control and management plane for enhanced trustworthiness and improved visibility across the network. In addition, the computing layer can be used with virtualization to provide commonly-used services within the network, including location and optional privacy modes.

A brief outline of the operation of the *MobilityFirst* protocol stack is given in Figure 2. As shown in the figure, at the top of the protocol stack there are multiple naming services which assign unique identifiers (the global identifier, GID) to all network-attached objects including mobile devices, sensors, content, or context. Once a network object has a unique GID, there is a distributed global name resolution service that runs on all the network routers which maintains the dynamic binding between object names and their current network addresses (or locators). The network addresses may have hierarchical structure similar to that in IP, or could be redesigned to achieve improved topological aggregation properties. These network addresses are used by the storage-aware routing layer below for the actual transport of data. As mentioned earlier, the *MobilityFirst* architecture uses storage-aware routing with large data storage at most routers (or wireless base stations and access points) intended to improve performance in the presence of time-varying channel quality and disconnections due to mobility. Storage-aware routing is also associated with the concept of segment-by-segment (or hop-by-hop) transport of data files between routers [20] in contrast to end-to-end transport protocols such as TCP which are in use today. The rest of this paper focuses on the design and evaluation of the adaptive storage aware routing algorithm being considered as a key component of this architecture.

B. Basic Storage Aware Routing Protocol

Storage-aware routing methods were proposed earlier as part of the Cache and Forward project at WINLAB [5], [6]. The key idea of the storage-aware routing approach is send content files (potentially ∼10MB to ∼1GB in size) from router to router in a hop-by-hop fashion with the option of interim local storage at routers when the downstream path is impaired or disconnected. This approach improves performance significantly relative to conventional TCP/IP because in-network storage helps to overcome periods of poor link quality or complete disconnection which would have otherwise resulted in transport protocol timeout and corresponding low throughput. Storage makes it possible to avoid transmitting large data packets to mobile users who currently have low bandwidth connectivity as long as there is an expectation of improved link quality in the future. Conversely, stored data can be opportunistically pushed to the intended recipient during periods of good connectivity helping to increase the overall utilization of network resources.

The protocol studied in [4] assumes storage is available at

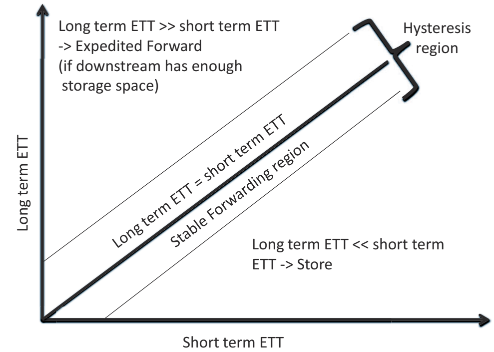

Fig. 3. Strategy for deciding to store or forward at routers in storage aware networks.

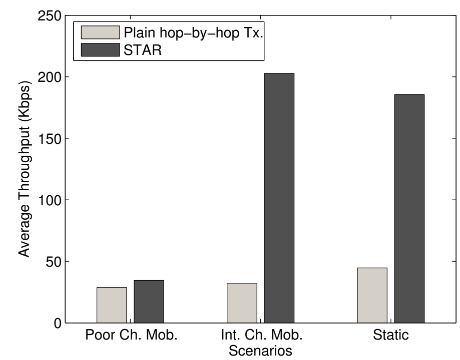

Fig. 4. Sample throughput results for basic storage-aware (STAR) routing in different mobile/wireless usage scenarios.

routers, and uses expected transmission time (ETT) [21] as the routing metric along with a policy to select paths and detect link quality. Each router maintains two routing metrics: a short term routing entry that has average ETT over a short duration (SETT) and a long term routing entry that records average ETT over a larger duration (LETT) for all links. The conventional routing region for the basic storage aware routing protocol [6] is as shown in the Figure 3, and can be described as:

$$SETT > LETT \Rightarrow Store; \quad (Path\ \ Quality\ \ Poor) \quad (1)$$

$$SETT \leq LETT \Rightarrow Forward \quad (Path\ \ Quality\ \ Good) \quad (2)$$

If the $SETT > LETT$, then it indicates that recently the channel is currently worse than the long term average provided by LETT. Hence, the protocol decides to store[1]

Results from a simple performance measurement done over a single hop with different types of wireless links is as shown in Figure 4. We consider three types of wireless traces, (1) a mobile traveling under very marginal coverage (*Poor Ch. Mob.*), (2) a mobile traveling between intermittent good and

[1] If multiple paths are available to the destination, the path selection decision involves an ordered list of paths with increasing SETT and considering whether to forward after balancing both SETT and LETT factors on candidate paths. We observe that when the $SETT << LETT$, the schedulers on the routers can greedily prioritize links with the best links for outbound transmission.

poor radio coverage (*Int. Ch. Mob.*), and (3) a static channel in poor radio coverage (*Static*) with a lot of human mobility in the background. In all three cases, we observe that the basic storage aware routing protocol (denoted as STAR) is able to opportunistically utilizes better short term paths, resulting in significant throughput gains (as much as ∼4-5x, comparable to gains reported in earlier papers on CNF [5], [6]) over simple hop-by-hop routing. As expected, the percentage throughput benefit is the highest when the mobile intermittently moves into a good coverage area from poor radio coverage. These gains in network performance motivated us to adopt storage aware routing as the baseline for intra-network routing in the *MobilityFirst* architecture. In the following section, we discuss enhancements to the baseline storage aware routing needed to address the needs of the project.

C. Additional Design Considerations for Routing

The *MobilityFirst* proposal aims to design all key protocol components in the core and the edge network to explicitly support mobility. In such cases, the routing protocol needs to be able to cope with a wide range of operating conditions across different devices. Specifically, the routing protocol needs to be able to make routing decision irrespective of the type of physical networks (wired or wireless), quality of links (good or poor), and storage capabilities of the device. In addition to these, the routing decision has to be made with minimal overheads and should be scalable. In the light of these requirements, we consider the following changes and additions to the basic storage aware routing protocol:

1) Support for multi-homing, multicast and anycast modes associated with anticipated mobility scenarios.
2) Support for multipath routing as a means to increase robustness in wireless edge networks.
3) Hierarchical aggregation of storage-aware routing information across inter-networks.
4) Adaptive control of the routing policy depending on network conditions such as link speed, storage, and transit traffic (if any).

The above requirements will involve a generalization of storage-aware routing to efficiently deal with emerging multi-homing and multicast/anycast modes as well as the need for internetwork aggregation necessary for scalability. In the rest of this paper, we focus on requirement #4 for a more general adaptive storage aware routing algorithm which is capable of responding to current network conditions including link quality fluctuations, available router storage and so on.

IV. Adaptive Storage Aware Routing (ASTAR)

The traffic load faced by a router is variable depending on: (1) Short and long term link conditions, (2) Network connectivity (e.g. some routers may be centrally located resulting in more transit load), and (3) Locally generated traffic may vary depending on the usage by devices connected through the router. Thus, considering this traffic load disparity across routers, and the fact that storage space at a router is limited and variable, we cannot use the same static decision rule for evaluating whether to store or forward the package at every router.

The decision process in the basic storage aware routing protocol is as described in equations (1), and (2). This can also be specified as follows:

$$SETT = K \times LETT \quad (3)$$

Here, we call the variable K as the *channel deterioration metric* since K is computed as $\frac{SETT}{LETT}$. Further, we propose,

$$if(K > Z) \Rightarrow Store \quad (4)$$

$$if(K \leq Z) \Rightarrow Forward \quad (5)$$

The new variable Z is referred to as the *decision factor*, since it plays a central role in the routing decision[2] In the above equations, when K = Z = 1, the decision process corresponds to the straight line the simple baseline storage aware routing protocol discussed earlier in conjunction with Figure 3. However, due to the disparity in operating conditions of different routers, we propose making the decision factor Z adaptive based on the internal operating condition of the router. In further discussion, we will elaborate how the addition of this decision factor Z to the basic storage routing approach can introduce flexibility in the routing policy.

A. Adaptive Decision Factor (Z)

The decision factor Z should ideally be chosen such that every router will try to limit the number of content drops due to the lack of available storage space. Hence, Z has to account for:

1) Traffic dependence: The routing scheme should take into account the traffic load before choosing a path or making a decision to forward or store.
2) Link speeds and congestion: The decision to load or store should also be dependent on the absolute speed of the links connected to the router as compared with the network load characteristics.
3) Storage space: The scale and size of each of the nodes acting as routers may vary depending on the device. This in turn will also decide the amount of available storage.

Apart from these requirements, the decision factor Z should preferably be based on locally available information to ensure scalability. We observe that instead of measuring each of the above mentioned parameters, we can use the residual storage space (S) as a single metric indicative of all of these parameters. Specifically, $S \propto \frac{(links\ speed,\ storage\ size)}{(load,\ congestion)}$. Hence, by making our decision factor Z inversely proportional to the locally measured residual storage space S, we can account for all these factors. As the residual space at the router decreases, either due to increased load or the inherent size of the storage cache itself, that router will be less likely to store and more likely to forward even when the link conditions are not as good as they are in the long term and vice versa.

[2] Here we focus on the store-and-forward decision after an end-to-end path has been selected based on a metric such as minimum total $SETT$ to the destination node.

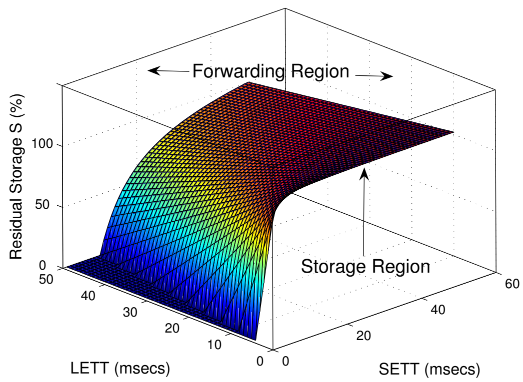

Fig. 5. The 3 dimensional decision space for adaptive storage aware routing. Space below or on the surface is the storage region, and above the surface is the forwarding region.

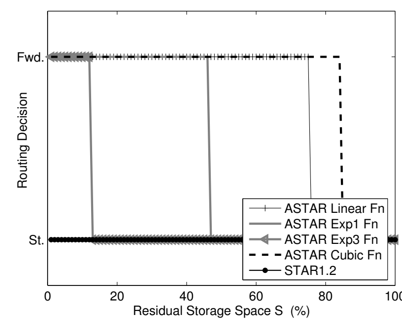

Fig. 6. Evaluation of the routing decision made by different protocols as a function of the residual storage space available at that router.

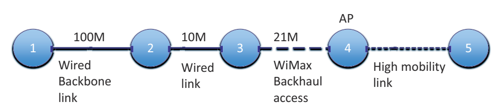

Fig. 7. Topology used for end - to - end evaluation of the proposed ASTAR modification to the basic storage aware routing protocol.

The exact mapping between the decision factor Z and the residual storage space can be implemented with different types of functions leading to different performance characteristics.

B. Mapping Function For Z

Let us denote the maximum value of storage desired, generally, at every router as S^{max}. This value can be selected as some maximum value, say $100 \times F^{size}$, the average network file size. Let us denote the maximum residual storage space at the router K as S_k^{max}. Let us denote the maximum value of the decision factor as Z^{max}. This is a network wide value and can be made equal to S^{max}. This value can be made static during hardware design or can be made dynamic, if updates are supported from other routers in the network.

The actual mapping between the decision factor and the residual storage space can be implemented by different functions. A simple linear function L, that maps the residual storage space at any router *k* to its decision factor Z_k can be given as:

$$Z_k = L(S_k) \tag{6}$$

$$Z_k = (Z_k^{max} - 1) \times (1 - \frac{S_k}{S_k^{max}}) + 1 \tag{7}$$

Other possible functions that we consider are two varieties of exponential functions, and a cubic function given as:

$$Z_k = Z_k^{max} \times exp(-1 * (S_k - 1)/(S_k^{max}/8)) \tag{8}$$

$$Z_k = Z_k^{max} - 0.000001 \times Z_k^{max} \times S_k^3 \tag{9}$$

It is observed that all these three functions will result in different behavior of the router, and will be discussed in further sections.

C. Routing Decisions

Before we start discussing the impact of using different mapping functions with ASTAR, we briefly describe the change achieved to the routing approach in the basic storage aware routing protocol described in Figure 3. Using the linear function described above, the routing region with our ASTAR mechanism becomes as shown in Figure 5. The area above the surface indicates a region for forwarding, and the area below can be used for storage. We observe that as desired, the decision to forward is made only when the SETT is relatively small as compared to LETT, or when the amount of residual storage is significantly high.

Examples of the decision space resulting from K=2 at the router with various different policies are shown in Figure 6. We see that the baseline storage aware routing protocol built with a default constant decision factor of 1.2 always makes the decision to store the file. In contrast, we observe that the adaptive storage aware routing (ASTAR) schemes would make different decisions based on the residual storage at the router. We see that the ASTAR scheme with the cubic mapping function has the most conservative policy towards storage, while the exponential policy based on equation 8 is more relaxed. Further performance evaluation for alternative mapping functions is presented in the evaluations in Section V.

V. Trace Driven Model Evaluation

In this section, we present a preliminary performance analysis of the proposed ASTAR mechanism. For the sake of discrimination, all results marked *STAR* will refer to the results obtained with the baseline non-adaptive storage aware routing protocol [6]. The results obtained with the enhanced storage adaptive routing strategy are marked as *ASTAR*.

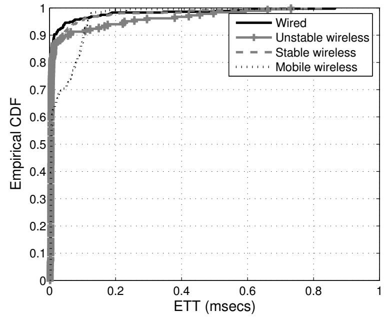

Fig. 8. Experimentally obtained cumulative distribution function of ETT measured on different links.

A. Evaluation Model

For this preliminary evaluation, we consider a simple linear topology with heterogeneous wired and wireless links as shown in the Figure 7. The four links, we consider two wired links and two wireless links. One of the wired links is a fast 100Mbps link, while the other is a relatively slow 10Mbps link. The remaining two links are wireless links. Among these the first link is a stable long haul wireless link like that provided by WiMAX for back haul access. The last link from node 4 to 5 is a very unstable wireless link typically seen from an 802.11 access point to a client.

To model each of the links in the heterogeneous topology realistically, we have used experimentally obtained ETT measurements[3] on these links to determine the end to end routing performance. The cumulative distribution function of the ETT measured across these different types of links are as shown in the Figure 8. We observe that the stable wireless link and the wired link have comparable measurements for ETT. The stable wireless link was measured between an 802.11 access point and a static client, while the wired link was measured between two networks within our lab. The unstable wireless link is measured by placing the client in an area of poor coverage with a lot of people moving around it. This unstable wireless link is used to model coverage for wireless clients in SOHO scenarios which are faraway from the access point. We see that the ETT measurements on this link vary more and are higher than those measured for the stable wireless link, and the wired link. Finally, the worst ETT measurements are seen for the mobile wireless link, where we walk within our lab with a wireless client associated with the access point through random paths. It is important to note that none of these measurements are intended to be comprehensive, but rather they serve as an indicator for typical variations that could be seen on these type of links. Hence, we will use the wired trace to model links between nodes (1,2), and (2,3) as shown in Figure 7. The stable wireless trace will be used for the link between (3,4). Finally, we will use the unstable static wireless trace and the mobile wireless trace for the link between node (4,5).

[3]The wireless measurements were measured at the ORBIT [22] site with a node configured as a WiFi access point, and the client emulated by a laptop. Link quality was measured using actual packet roundtrip times under the different scenarios described here.

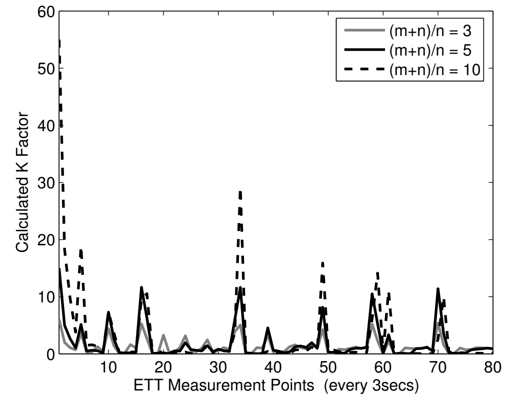

Fig. 9. Results plotting the K factor ($\frac{SETT}{LETT}$) as a function of the measured ETT. Different values of K are obtained by using different window sizes for SETT and LETT. m+n denotes the window size for LETT, while n denotes the window size for measuring SETT.

B. Effect Of Link Conditions On K

Figure 9 shows the calculated value of K achieved by using different number of samples of the ETT to generate SETT and LETT. $m+n$ denotes the window size for LETT, while n denotes the window size for measuring SETT. Hence, $\frac{m+n}{n} = 3$ denotes that the sample size of the LETT window is thrice that for the SETT measurement. Further we also plot for $\frac{m+n}{n} = 10$, which indicates that this type of measurement gives higher preference to historical values as opposed to newer measurements, thus presenting an even better view of typical channel conditions seen by the wireless node. This is clearly evident from the plot where we see that K is highest for $\frac{m+n}{n} = 10$, since averaging LETT over a larger window provides a better feedback that the link usually has low ETT, and the routing protocol would be better of storing the content (if any).

C. ASTAR Performance

We consider two experiments which will measure the performance of the ASTAR mechanism over the basic storage aware routing protocol (STAR) while transmitting a file from router/node 1 to 5 along the linear topology described in Figure 7.

The goal of the first experiment is to understand the baseline performance of the ASTAR mechanism as compared to that of the baseline non-adaptive storage aware routing protocol (STAR). To do this, we test the performance with the last hop (node 4 to node 5) being modeled by two different wireless channels while operating with different available residual storage space. Specifically, since we are modeling the last hop as an unstable wireless link, we consider the wireless trace with a static position with poor coverage (*Static*) and the ETT trace with indoor mobility (*Mobile*). Load at the last hop is simulated by changing the residual storage S, which

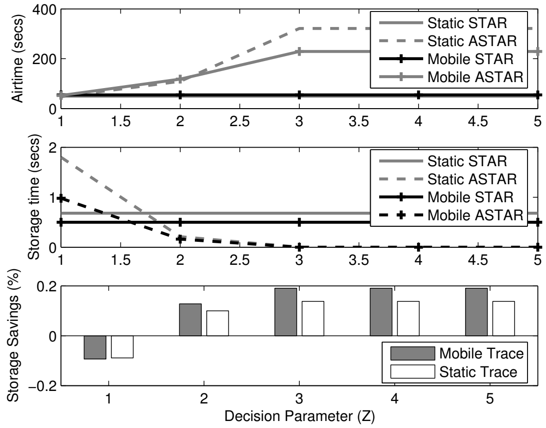

Fig. 10. Preliminary results showing the performance with ASTAR vs. basic storage aware routing protocol (STAR).

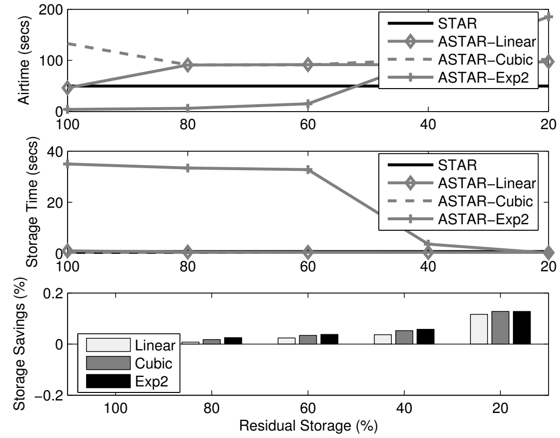

Fig. 11. Performance with the ASTAR modification for routing vs. basic storage aware routing protocol (STAR) for different mapping functions of Z parameter.

in turn changes the decision parameter (Z). The result shows performance measured in terms of three metrics. The airtime result shows the aggregate airtime required for transmission of the file from node 1 to node 5. It should be noted that this airtime does not indicate the finishing time of the file transfer from node 1 to 5, but rather the amount of channel time used[4]. The storage time measures the amount of time the content spent in storage before reaching the destination node 5. Finally, the storage improvement or savings measure the difference in storage available with the ASTAR mechanism as opposed to that obtained with the basic storage aware routing protocol.

The results from this experiment are as shown in the Figure 10. As expected we observe that the performance of the basic storage aware routing protocol (marked as STAR) is independent of the residual storage on the node and is purely a function of the channel conditions as presented by the ETT trace used for node 4. In case of ASTAR we observe that for both the *Static* and *Mobile* ETT traces, the storage time decreases, and the transmission time increases as the available storage at the node 4 decreases (indicated by an increasing value of Z, since $Z \propto \frac{1}{S}$). We also observe that initially when a lot of residual storage is available (Z=1), the ASTAR mechanism decides to store even when the channel deteriorates slightly, while the basic storage aware routing protocol has a fixed policy to store only when the channel deteriorates up to a certain threshold. This results in low storage and transmission times for ASTAR (for Z=1). However, this also results in lower residual storage availability for ASTAR as compared to STAR. When the residual storage at node 4 decreases significantly, ASTAR decides to forward even when the channel is temporarily poor at node 4, resulting in increase in residual storage space of up to 20% of what can be achieved with the basic storage aware routing protocol. It is very important to note that the improvement in residual storage will always come at the cost of more airtime to transmit the file, since it involves forwarding even when the channel may be deteriorated. However, the intention behind the ASTAR mechanism was not choose a particular policy on routing, but, rather to show that using such a mechanism, the routing policy can be made truly storage-aware. The aggressiveness of such ASTAR mechanisms can be controlled by changing the mapping function, as will be shown in the next experiment.

[4]This distinction between channel airtime and transfer completion time is important because a file transfer can result in the consumption of more channel airtime, and still finish faster since it does not spend much time in storage. All our results will plot the channel airtime and storage time separately.

In the second experiment, we repeat the scenario in the previous experiment. Instead of using a fixed linear function to map the residual storage space to Z, we evaluate the impact of using different mapping functions on the overall performance of the ASTAR mechanism. Results from this experiment are as shown in the Figure 11. As seen earlier, the basic storage aware routing protocol (STAR) always results in a static performance, and the results remain unchanged with the amount of residual storage at the router.

We observe that ASTAR with the exponential (*Exp2*) function is the most cautious with transmission bandwidth and almost always decides to store the file when it has a high amount of available storage space and the channel deteriorates even slightly. This results in very low transmission airtime for the exponential scheme. However, this also increases the end to end delay since the storage time is higher than all the other schemes, which have small but non-zero storage times. We also observe that as the residual storage at the router drops, the exponential function results in forwarding almost all the time resulting in high transmission airtimes. The cubic mapping function and the linear function on the other hand tend to favor transmission over storage. Thus we observe that using different mapping functions we can select different policies towards storing as a function of transit traffic through the router. Note that ASTAR does not advocate a particular policy, but rather provides a mechanism by which the designer may choose between lower airtime and higher residual storage by appropriately tuning the mapping functions.

D. Discussion

Neighbor Count For Routing Decisions: An important metric that will be considered in future revisions of this work are the use of neighbor count for wireless devices. The value of the decision factor Z can be additionally made inversely proportional to the number of neighbors, thus utilizing a slower link only when the number of wireless neighbors is small.

Auto-tuning based on evaluation of K^{max} We also observed that some mechanisms will be needed to ensure that $Z^{max} = K^{max}$, to ensure that the routing decisions are made on the correct area of the intersections of K and Z. This can be done by ensuring that routers update these values when they exchange messages with the baseline routing metrics like hop count and ETT measurements.

VI. Conclusion And Future Directions

This paper presented an overview of the proposed *MobilityFirst* future Internet architecture with particular focus on the storage-aware routing protocol as a key component. The principle of storage-aware routing based on a two dimensional (short-term, long-term) path metric has been explained, and it is shown that this approach can provide significant improvements in example wireless/mobile usage scenarios. In addition, this work proposes a new adaptation mechanism for the fowarding/store decision at routers by introducing the so-called decision factor, Z. The proposed adaptive storage-aware routing (ASTAR) metric is evaluated for example heterogeneous mobile-wireless scenarios using a trace-driven simulation approach. The ASTAR mechanism offers the capability of adapting to variations in link quality, available storage and traffic levels, resulting in improved network performance and/or reduced router storage requirements. We conclude by noting that adaptive forwarding decision algorithm is only one of the many design items that need to be considered for the routing protocol in the *MobilityFirst* project as a whole. In future work, we plan to describe how the storage-aware routing protocol can be extended to support the key requirements of multi-homing and multicast. Another important issue to be considered in the future is the aggregation of storage routing updates at the inter-network level. We also plan to report on real-world performance measurements with storage-aware routing operating on the ORBIT and open GENI WiMAX experimental networks deployed at WINLAB.

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