IMPACT: International Journal of Research in Engineering & Technology (IMPACT: IJRET)
ISSN(E): 2321-8843; ISSN(P): 2347-4599
Vol. 3, Issue 3, Mar 2015, 1-10

A DESIGN OF A CACHING STRATEGY FOR RURAL WIRELESS MESH NETWORK (WMN) DEPLOYMENT

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ABSTRACT

Wireless Mesh Networks (WMNs) have high potential to provide broadband access for rural communities in developing countries. However, existing networking concepts used to build WMNs are not designed to take specifics of these deployment environments into account especially a high degree of the topology variation and bandwidth limitations. Further, equipment deployed has to be very cheap, often battery powered and operated by non-experts all leading to frequent node failures and resulting in availability constraints.

Data availability for the outlined scenarios can be improved employing data caching. Topology changes and link outages have far less effect if a cache can provide the data. Users of a rural community tend to access similar data sources and, thus, caching can be highly efficient given the small scale of rural deployments. Recent technology advances also make it possible to include large amounts of storage space (in the form of flash memory) in even cheap network devices as found in rural areas of developing countries.

In this paper, we present a data caching strategy for rural WMN deployments in developing countries. Different to many existing strategies we exploit the fact that every node in the network can cache data, and we exploit the wireless nature of the network and use overhearing of transmissions to populate caches. Finally, we present a design for a Distributed Over-heard Object Caching Approach (DOCA) while the future work will evaluate the capability to increase data availability under a typical scenario in developing countries with severe budget constraints.

KEYWORDS: Distributed Caching, Data Availability, Network Reliability, Over-Hearing and Resilience

1. INTRODUCTION

WMN deployments in developing regions especially Africa faces challenges such as single gateway access, small bandwidth, the VSAT communication asymmetry, resource scarcity and power instability that exacerbate performance degradation. Mainly, the problems with Scalability, Availability, Reliability and Resilience (SCAR-2) become critical under dynamic topologies [1]. The need to sustain data availability, network resilience, and energy optimization becomes necessary. However, one can exploit content similarity due to close community ties to implement content caching to improve the network response time for access for rural dwellers.

Caching can reduce data access delay, message communications cost, increased data availability and also optimize both resources (such as battery energy) and bandwidth utilization [2]. Existing caching technologies (based on centralized, clustered or on-path approaches) for urban WMN implementations are not directly relevant the already outlined rural context that also uses cheap and computationally constrained devices under dynamic scenarios.

In this paper, we present a new caching strategy that exploits advances in technology to provide nodes with high-capacity and inexpensive memory devices such as secure-digital (SD) and flash memories. Specifically, a proposition that jointly implements caching of overheard data as well as employing random-path techniques becomes necessary.

Different to many existing strategies we exploit the fact that every node in the network can cache data, and we exploit the wireless nature of the network and use overhearing of transmissions to populate caches. The approach further exploits over-hearing to achieve homogeneity of cache contents. Specifically, a distributed overheard-object caching method (DOCA) is presented to improve the performance efficiency of rural WMNs. It draws its motivation from the studies on random-path cache request (RPCR) technique [3] and overhearing of caches [4], which do not consider rural implementations. DOCA combines the abilities for nodes to overhear transmissions with a modified-RPCR technique, which uses a Minimal Spanning Tree (MST) protocol to exploit path redundancy under topology variations.

The use of all nodes as caches reduce the impact of the node exclusion, which otherwise becomes significant for implementations that adopt clustering or centralized caching technique under power constraints and domain characteristics. Further, the design integrates mechanisms for cache consistency using a light-weight inter-nodal communication to ensure homogeneity of cache contents and an energy-efficient cache update mechanism administered during off-peak periods. We assume that by default, a node can determine the cache misses relating to specific data items and subsequently request for them from the nearest available cache. Also, the design assigns, to each object or data item, a unique identifier (id).

The paper organization is as follows. Section 2 examines a few of existing work on caching in multihop wireless networks. Section 3 describes the network architecture and the design assumptions. Section 4 motivates the design of DOCA while Section 5 presents a first view analysis of the effectiveness of the DOCA algorithm via simple illustration. Section 6 provides an overview of DOCA under construction. Section 7 briefly highlights the conclusion and future direction of this work.

2. LITERATURE REVIEW

Co-operative caching has proven performance benefits for reducing access latency, increasing data availability and energy conservation. Tang et al. present a distributed benefit-based data caching to replicate data using an approximate polynomial-time algorithm [5]. [6] evaluates the performance of three distributed caching algorithms namely CacheData, CahcePath and HybridCache in ad hoc networks based on access frequency on the assumptions of unrestricted power and cost availability. These are non-trivial factors in the rural domains. The study in [7] investigates the problem of adaptive energy cache placement technique modeled as facility location problem [8] for a single data item in ad hoc networks. Reference [9] used an asymmetric cooperative caching method to enhance data access for a p2p WMN, and also characterize the influence of effects of different MAC layers on the efficiency of the cooperative cache.

Alasaad et al. exploits over-hearing to implement a content caching and replication schemes that improve performance efficiency for file sharing in P2P applications over WMNs [10]. Reference [11] offers the content caching and replication strategies for WMNs. Wu et al. [12] also utilized over-hearing to optimize cache placement and discovery to reduce data access cost and access latency. The study in [13] implements a hierarchical approach to cooperative caching for WMNs. [15] utilizes a clustering method [14] for CacheRescue for Mobile Ad hoc Networks (MANETs). To offer reductions in traffic overhead in the gateway and network e2e delay (improved data access), Wu and Huang implements a clustered approach to caching at the cell and network level [16]. The study in [3] investigates a “random-path” caching technique that optimizes network load and gateway congestion over a static WMN in an urban area.

The use of overhearing can offer improvements for the TCP throughput degradation that results from link instability, MAC interference and environmental noise [4]. "Ditto" is an opportunistic caching strategy for a WMN that also employs caching overhead data to enhance data access and mitigate gateway congestions. The mechanism offer discrete transmissions (suppress duplicate transmissions), which provide high capacity utilization and performance enhancement. However, Ditto performs content overhearing at the granularity of 8-32KB chunks employing a DOT protocol, which is an unconventional pull-based transport scheme. The system does not accommodate short flows and dynamic content-based flows, which are prevalent on the web, and enterprise flows. Furthermore, it does not efficiently utilize overhearing due to the poor reconstruction of chunks as well as the lack of consideration to accelerating downloads using a piece diffusion strategy.

Motivated by a few of the drawbacks, [17] implements IP-layer content overhearing technique called Refactor that uses a hybrid model data structures and redundancy elimination techniques. Specifically, the design exploits content overhearing at the sub-packet payload level by integrating IP-layer redundancy elimination as well as a network coding platform. The wireless nodes in REfactor can eliminate packet redundancy at the sub-IP layer for cache objects at a much finer granularity than Ditto; however, without considerations for a rural implementation. Many of the works described are not energy-efficient, like the investigation in [5] because of the implementations cover settings with stable power grids.

3. NETWORK ARCHITECTURE AND ASSUMPTIONS

The wireless mesh network under consideration typically fits most rural deployments investigated in the authors' earlier papers especially in rural Africa such as Peebles valley mesh, Macha Network, and Sengerema mesh network. Typical of all these rural implementations is the coverage of small geographical landscape, low bandwidth, power issues, resources constrained devices and environmental variations. Moreover, the cost of interconnectivity also limits the deployments to a single radio and gateway models as well as restriction of the use of VSAT connectivity.

The diagram in Figure 1 depicts the network architecture under consideration within the paper scope for the proposed caching system for a rural WMN implementation. The system is depicted using an undirected graph G = (V, E) where 'V' is the set of vertices representing the network nodes and the set of weighted edges, 'E' denotes the wireless communications links.

In this architecture, we expect a node to communicate using wireless transmissions with all other nodes that are wirelessly connected. The implication is that each node will direct wireless transmissions to all other nodes within its transmission region. These set of nodes are described based on the degree or valency of each node. For instance, based on the out-degrees of the nodes, the semantic for object caching in the system is shown in the diagram and later described.

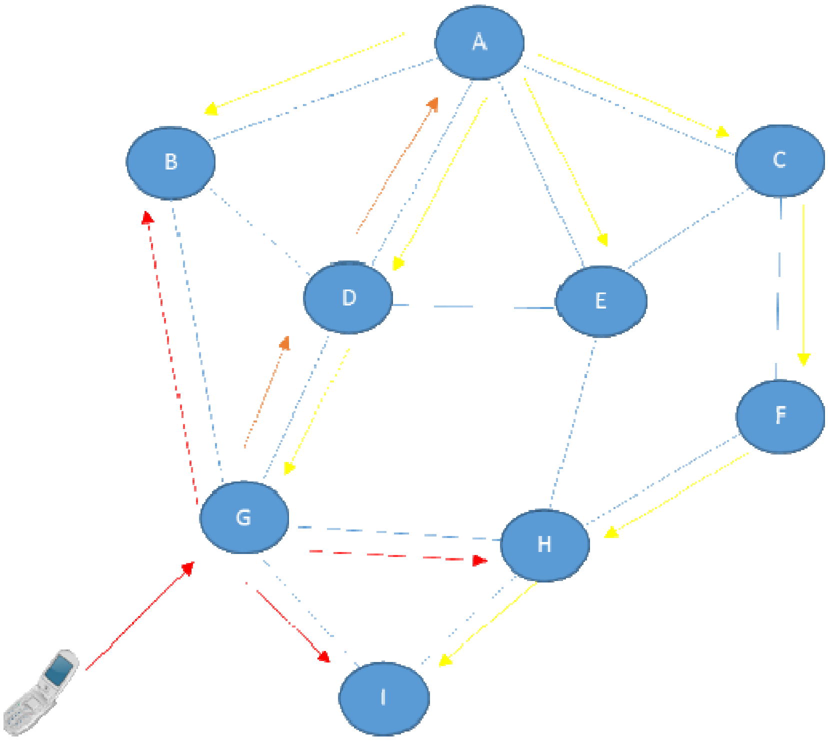

Figure 1: A Rural WMN Architecture

The system assumes a static WMN two-tier structure consisting of nodes otherwise referred to as Mesh Routers (MRs) and the Mesh clients (MCs). The MRs connects to form the mesh backbone and also serves the purpose of cache nodes that communicates wireless over multi-hop paths. Therefore, the function of the nodes for data access as well as traffic forwarding requires the use of a dual radio technology as against the utilization of a single radio prevalent in earlier rural WMN deployments. Moreover, the choice of dual radio is motivated by upgrades to many of the real-life WMN deployments such as the Wray community mesh network. The configuration uses the radio technology based on the IEEE 802.11 Wi-Fi standard. Furthermore, the nodes have access to unbounded memory capabilities leveraging the advances in technology with the proliferation of inexpensive and high capacity storage devices such as the secure-digital (SD) and flash sticks. Consequently, the node has functionalities for traffic forwarding as well as a cache location. The architecture also utilizes one of the nodes as the connection to the wired the internet, which serves as the gateway (GW) node.

Another basic assumption is that MCs are static or having little degree of mobility since the consideration is a rural WMN scenario where the local community is bounded together by several factors including social, religious and family ties. Moreover, the client base of rural localities prefers to associate with MRs within their proximity to conserve energy. Further, unlike, other caching implementations, the choice of using MCs are cache nodes as a result of limited resources makes the selection of MCs as cache nodes unattractive due to budget constraints in these settings. In addition, we assume that the transport protocol utilized is the internet-based TCP protocol for data exchange. The demand for user applications places requires that multiple data items can be accessed by the mesh routers (nodes). The small scope of rural WMN design limits the data items for consideration because of the utilization of every node in the mesh network as potential caches in the resource-constrained environment. There is no need to locate the source of any data item in this case, and the overhead of searches are very minimal since any node serve as the cache.

Moreover, the primary source of any missing item is the gateway node, which also doubles as a cache node for simplicity. The design benefits from reaching a homogenous state in terms of cache items; particularly, the use of overhearing greatly allow the spread of multiple data items across the network nodes.

4. MOTIVATING CACHING APPROACH

The motivation for this work is as a result of the numerous challenges that faces WMN implementations in the rural domains. The constraints include inadequate bandwidth, power instability, communications asymmetry, VSAT connections and single gateway limitations. Consequently, data availability and performance throughput becomes a problem due to frequent topology variations and use of battery powered devices. An efficient solution to improve data availability and optimize performance vis-à-vis limited bandwidth motivates the design of the network architecture shown in figure 1. Specifically, the centralized and clustering caching techniques employed for urban WMN implementations is unattractive for the rural setting characterized by scare resources (such as low bandwidth, memory, and nodal energy). Moreover, power instability and gateway congestion exacerbate the problems of network reliability and usability due to high in-network delays.

Sequel to challenges mentioned earlier, the proposed caching design jointly investigates the use of RPCR and overhearing to improve WMN performance. Also, it implements a light-weight inter-nodal communication semantic that can significantly enhance the convergence of network state in terms of cache homogeneity is realizable in nearly non-zero time. Specifically, exploiting path redundancy via a minimal spanning tree (MST)-based RPCR will optimize network load and gateway congestion while data availability significantly increases through over-hearing. Moreover, the technique will also enhance network throughput as well as optimize bandwidth utilization.

Leveraging the above benefits motivates the design of DOCA to meet the requirements of rural WMN deployments with rapidly changing topology.

5. OVERVIEW OF DISTRIBUTED OVERHEARD-OBJECT CACHING APPROACH (DOCA)

A wireless client within the transmission range of an edge mesh router (EMR) initiates an object access request using an RPCR technique that implements an MST algorithm if a cache miss arises on the associated EMR. Otherwise, it sends the data requested back immediately to the client (cache hit). The caching technique administers the syntax if the network is idle; otherwise, the EMR sends a multicast via overhearing to other nodes attached wirelessly to the specific EMR. The object request passes through intermediate upstream mesh nodes towards the uplink gateway. When receiving the cache request, the intermediate upstream nodes also check for a cache miss or hit to determine the cause of action until it gets to the gateway.

The caching system communicates replies to new object access request from the gateway back to the client via the EMR using overhearing. Specifically, replies are sent from the gateway using a modified-multicast technique to all nodes wirelessly connected based on the degrees of the nodes starting from the gateway. Subsequently, every other node that overhears the transmission of the reply also multicast to all nodes connected based on their degrees. This recursive semantics iterate until the destination EMR through, which the request emanates, gets the reply. Over this process, each recipient node caches the object item and in this way the cache spreads over the entire network node. Furthermore, the semantics of DOCA implements a light-weight cache consistency procedure with low communication overheads to ensure cache homogeneity. The replies fetched through the gateway are propagated back to the requesting client when a cache hit occurs via on-path and the modified-multicast over-hearing method across available intermediate nodes until it reaches the client. The client only receives the first reply to the request and discards all other replica messages. In order words, each intermediate nodes and nodes within the transmission region caches the object or file received in response to a cache request initiated by the client. Finally, to ensure cache content correctness, the rural WMN caching system arbitrates the updates of data items on-demand especially during off-peak times.

Typically, selecting a network architecture in this work is motivated based rural requirements. The description of the DOCA algorithm in section four is listed as follows. The Listing of the DOCA algorithm is as follows:

- BEGIN (***Object Request***)
  - **if** request for object “x” is received by an EMR **then**
  - **if** a first object “x” request **then**
  - Compute a RPCR_MST to GW.
  - Transfer object to the requesting client,

  Multicast-Overhearing Nodes until it gets to EMR of requesting client,
  - EMR caches Object “x”, passes it to Client X
  - Mark object “x” as active.
- **else**
  - **if** requesting an object “already cache, fetch from the EMR, otherwise,
  - ➢ send multicast request to all over-hearing nodes to fetch the cache,
  - Send cache request-reply using multicast techniques to all overhearing Nodes until it gets to EMR of requesting client, (Caches are not stored except it is missing).
  - ***Cache Consistency***
  - A given EMR/MR request for missed cache objects from all over-hearing nodes,
  - Content comparison using designated Id returns any missing object via a multicast from a node based on its degree.
  - Only the needed object is cache as other multiple messages are discarded.
  - ***Cache Update***
  - Coordinated by the gateway (GW)
  - object update modified using its unique ID and Propagated to the other mesh routers/EMR,
  - GW sends a multicast of the object update to all wirelessly connected nodes **else**

- Each MR/EMR only accepts one message for the update and discards the remaining.
- End

6. DOCA ANALYSIS

Based on the network model shown in figure 1 and the description of the semantics, an apt review of DOCA in comparison to on-path caching techniques is shown in the table 1 and table 2. Specifically, a consideration for object access from the mesh client through any node referred as the edge mesh router (EMR) (G in this case) as well as other EMR with the exception of the G and the gateway node A is shown. Following the central design philosophy of DOCA; the use of random–path specified with the implementation of a minimal spanning tree (MST) protocol to determine random paths following topology variation as well as the use of overhearing exploiting the wireless broadcast medium for cache request if a new data access request as well as replies to object access request.

Table 1: Client Access via Other EMR Routers Except G and A

	DOCA	ON-PATH
	Hop Distance	Hop Distance
Node B	1	1
Node C	1	1,2,3
Node F	1	2,3
Node H	1	1,2,3
Node I	1	1,2,3,4

Table 2: Client Access via EMR G

	DOCA	ON-PATH
Node A (GW)	1	1
Node B	1	
Node C	1	
Node D	1	1
Node E	1	
Node F	1	
Node G	1	1
Node H	1	
Node I	1	

The request for the object “X” through G requires the edge mesh router (EMR) G to broadcasts the object request to B, D, H and I. Otherwise, if it needs a new data item it computes an MST path via D to reach the gateway node A, which are shown by the red arrows. Similarly, the response to the object access employs the ability of nodes to overhear transmissions from other nodes within their wireless range. In this case, the data object “X” is broadcast from the Gateway “A” to other nodes based on its degree, hence, sending the object to nodes B, C, D and E (overhearing nodes of A) shown with the yellow lines. The DOCA semantics implies that recursive broadcast by each of these overhearing nodes until the reply gets to the initiating client. In other words, B broadcast to A, D and G; D also broadcast to B, A, E and G; similarly, E broadcast to A, D, C and H while C Broadcast to A, E and F.

Sequel to the above, the object requested speeds in nearly zero-time across all the nodes in the network. The avoidance of network congestions requires a design that implement data structures to allow each overhearing nodes to suppress duplicate transmissions from nodes within its transmissions region by discarding other replies once it receives one. Specifically, data items have identifiers that will allow for this process using simple basic searching and comparing techniques. The choice of a minimal time-to-live (TTL) will also help. Moreover, the DOCA design implements function for ensuring cache homogeneity to complement any missing object access on the part of over-hearing objects. The use of a central update scheme at the gateway node A simplifies the process and later disseminates the updates on identified objects at off-peak periods. In the event of node exclusion resulting from power failures, software glitches, hardware malfunctions and environmental variations, the mesh invokes the self-reconfigurability and self-healing capabilities. Subsequently, it allows for the continuing usage of overhearing within the subsisting network topology.

7. CONCLUSIONS

Several constraints such as low bandwidth, gateway congestions, power instability, backhaul restriction, and resource limitations affect data availability in rural WMN deployment scenarios. Given the above, the performance of rural wireless mesh networks becomes challenging especially due to inadequate bandwidth. To improve the performance efficiency of these network test cases requires efficient caching techniques different to that used for urban scenarios.

Consequently, the work proposes a design for a Distributed Over-heard Object Caching Approach (DOCA) that combines RPCR techniques (based on MST) with overhearing for increased data availability and network reliability. Also, the design will implement a light-weight scheme for the convergence of network state in terms of homogeneity of cache contents across all nodes.

While, it is impossible to achieve 100% data consistency concurrently due to unavoidable packet loss resulting from link instability and connection failure; the overlap of time makes content homogeneity realizable in nearly non-zero-time. The current investigation offers the analysis of the caching strategy, which shows that for the typical network architecture outlined; the degree of data availability remains significant. The successful implementation of DOCA offers network availability and reliability with the data spread over the use of on-path and random-path cache request due to robustness and adaptability to topology variations. Specifically, the probability, given node availability, is that after the first broadcast approximately 0.5 (excluding the gateway) of the total number of nodes have access to the object whereas the on-path only achieves a fraction of approximately 0.25.

The fraction of data homogeneity with respect to the network increases after the second level broadcast and over-hearing to about 0.85 or more for any outlined network scenario. However, under dynamic scenarios, the proposed caching system is still able to achieve a steady-state homogeneity substantial for high data availability in the rural test-case. The proposed caching system, if efficiently administered, will afford the deployment of a simple, robust and scalable rural WMN. Notably, it offers the capability to increase data availability under a typical scenario by increasing the memory storage of network nodes in developing countries with severe budget constraints.

To investigate the effectiveness of this caching system especially for scalability while increasing data availability and network reliability; the future work targets the experimental evaluation of DOCA via simulation analysis.

ACKNOWLEDGEMENTS

The author thanks all those who offered advice on this work especially my doctoral tutors; Dr. Utz Roedig, Dr. Christopher Edwards and Dr. Nicholas Race.

REFERENCES

1. Ajayi, Ayomide, Utz Roedig, Christopher Edwards, and Nicholas Race. "A survey of rural Wireless Mesh Network (WMN) deployments." In Wireless and Mobile, 2014 IEEE Asia Pacific Conference on, pp. 119-125. IEEE, 2014.
2. H. Chen, Y. Xiao, On-bound selection cache replacement policy for wireless data access, IEEE Transactions on Computers 56 (12) (2007) 15971611.
3. Sangwongthong, Tanachai; Siripongwutikorn, Peerapon, "Proxy caching in wireless mesh networks," Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2012 9th International Conference on, vol., no., pp.16-18, May, 2012 doi: 10.1109/ECTICon.2012.6254224
4. F. R. Dogar, A. Phanishayee, H. Pucha, O. Ruwase, D. G. Andersen, "Ditto: a system for opportunistic caching in multi-hop wireless networks," Proc. of Mobicom'08, pp. 279–290, 2008.
5. B. Tang, H. Gupta, and S. R. Das, "Benefit-based data caching in ad hoc networks," IEEE Transactions on Mobile Computing, vol. 7, no. 3, pp. 289–304, 2008.
6. L. Yin and G. Cao, "Supporting cooperative caching in ad hoc networks," IEEE Transactions on Mobile Computing, vol. 5, no. 1, pp. 77–89, 2006.
7. P. Nuggehalli, V. Srinivasan, and C.-F. Chiasserini, "Energy efficient Caching strategies in ad hoc wireless networks," in Proceedings of the ACM International Symposium on Mobile Ad Hoc Networking & Computing (MobiHoc), October, 2006, pp. 25–34.
8. C. Swamy, and A. Kumar, Primal-dual Algorithms for Connected Facility Location Problems, in Proc. of APPROX, 2002.
9. J. Zhao, P. Zhang, G. Cao, and C. R. Das, "Cooperative caching in wireless p2p networks: Design, implementation, and evaluation," IEEE Transactions on Parallel and Distributed Systems, vol. 21, no. 7, pp. 229–241, 2010.
10. A. Alasaad, S. Gopalakrishnan, and V. Leung. Content caching and replication schemes for peer-to-peer file-sharing in wireless mesh networks. In GLOBECOM Workshops (GC Wkshps), 2010 IEEE, pages 1707 {1711, Dec. 2010
11. S. M. Das, H. Pucha, and Y. C. Hu, "Mitigating the gateway bottleneck via transparent cooperative caching in wireless mesh networks," Ad Hoc Netw., Elsevier Science Publishers B. V., vol. 5, no. 6, pp. 680–703, 2007.
12. W. Wu, J. Cao, X. Fan, "Design and Performance Evaluation of Overhearing-aided Data Caching in Wireless Ad Hoc Networks", IEEE TRANSACTIONS ON PARALLEL AND DISTRIBUTED SYSTEMS, VOL. 24, NO. 3, MARCH 2013
13. T. K. R. Nkwe, M. K. Denko "Self-Optimizing Cooperative Caching in Autonomic Wireless Mesh Networks", 14th IEEE Symposium on Computers and Communications (ISCC 09)–Sousse, pp. 411- 416 Tunisia, 2009.
14. J. Tian and M. K. Denko, "Exploiting Clustering and Cross-Layer Design Approaches for Data Caching in

MANETs," Proceedings of the IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMOB 2007), pp. 52-52, 2007.

15. T. K. R. Nkwe, M. K. Denko “Efficient Cooperative Caching with Improved Performance in Wireless Mesh Networks”, IEEE Communications Society (IEEE ICC), 2010.
16. Zeigang Wu and Yifei Huang, Hierarchical Cooperative Data Caching for Wireless Mesh Networks, IEEE/IFIP International Conference on Embedded and Ubiquitous Computing, 2010
17. Shen, Shan-Hsiang, Aaron Gember, Ashok Anand, and Aditya Akella. "REfactor-ing content overhearing to improve wireless performance." In Proceedings of the 17th annual international conference on Mobile computing and networking, pp. 217-228. ACM, 2011.