A Fuzzy Content Centric Network Architecture for Real-time Communications in MANETs

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***Abstract*— Most practical applications of Mobile Ad hoc Networks (MANETs), such as Military Operation, Disaster Recovery, Tactical and Emergency Operation, Conference and so on, are built around real-time group communications. But distributing contents in those scenarios where multiple users actively take part in real-time communications is a great challenge primarily because of the frequent movement of the nodes, long multi-hop paths, congestion of the network and short battery life of wireless devices. As a result, content distribution in those scenarios becomes a multi-constraint problem. In this paper we argue that in order to address this problem, we need to decouple content from location in MANETs so that we can control it more flexibly; and we need to bring a node management approach that is capable of rearranging nodes adaptively. Therefore, we propose a fuzzy content centric network architecture and through experiments show that it performs better than the conventional IP network in MANETs.**

Keywords- Mobile Ad hoc Networks, Content Centric Network, Real-time, Fuzzy-logic

I. INTRODUCTION

Computer Networking has evolved greatly from its originating form. In fact, it was not invented for sharing content. Instead it was created to connect and share distributed resources and therefore, built around the host-to-host communication architecture. However, today the majority of network interactions are content oriented. Client devices request content and servers provide requested data. One of the important aspects during those interactions is that users only care for content and remain oblivious to its location. This clearly suggests that the next generation networking will be more focused on *what* rather than *where*.

This concept is especially important in Mobile Ad hoc Networks (MANETs). MANETs are complex distributed systems with mobile nodes having limited resources, different degree of mobility, wireless communication capability and necessity of multiple hops to transfer end-to-end data due to shorter radio transmission range. It is evident from this nature that tracking specific nodes for specific content is not an appropriate approach. The task becomes more challenging when such networks deal with real-time data, for example, a conference hall, lecture theatre, military or police operation, disaster rescue etc. where a group of people simultaneously exchange audio-video data amongst themselves. In those scenarios, challenges occur not only because of the frequent movement of the nodes, but also due to huge traffic load on the networks and short battery life of wireless devices. This lays the foundation of a classic multi-constraint problem.

This paper is focused on the design concept of a new network architecture independent of existing IP network. After investigating the problem carefully, we introduce an adaptive content centric network as an effective solution. The contributions of the study are two-fold – firstly, we decouple content from its location and establish an architecture that discovers content in a location-agnostic manner; and secondly, we introduce a fuzzy system that adaptively arranges nodes.

The rest of the paper is organized as follows: the related work is reviewed in section II, section III presents the proposed network architecture, section IV describes the operation of the proposed architecture, section V presents evaluation and results, and finally this paper concludes in section VI with some brief future ideas.

II. MOTIVATION AND RELATED WORK

This paper addresses a multi-constraint content delivery problem in MANETs while operating in emergency scenarios and dealing with real-time data. Previous proposals from the area of computer networking which tried to solve this problem can be divided into two broad categories: solutions within conventional IP network and solutions that are derived from a non-IP domain. Though the proposed work in this paper is a non-IP based approach, but it is motivated by works from both sides on the divide. Through a comprehensive review, this section describes the motivation of this work, contrasting existing proposals, their shortcomings and the need for an alternative solution.

Classically multicasting has been considered a solution to the problem where multiple nodes receive the same data from a single source or exchange data within a group. IP Multicast[1] was the first protocol to provide multicast support in MANETs. Though this protocol was proposed more than two decades ago, it still remains operational both in wired and wireless networks. In IP Multicast, a source node transmits packets to a multicast group using a single address from the D-class address space i.e. 224.0.0.0 to 239.255.255.255. These addresses are, in fact, responsible for identifying receiver groups. By using a group management protocol called IGMP (Internet Group Management Protocol), an individual receiver can inform the

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network when it intends to join a group. The network in turn runs the multicast routing protocol that is significantly different than its unicast counterpart. IGMP is also used to create and maintain a logical distribution tree that is rooted at the source and goes down the network where group members exist via a shortest loop-free path. A multicast router maintains inbound and outbound state of each source and group pair that it becomes aware of. However, this tree-based group management is the main disadvantage of IP Multicast. It is not suitable for scenarios where its tree-structure is subject to a rapid readjustment due to frequent changes in topology.

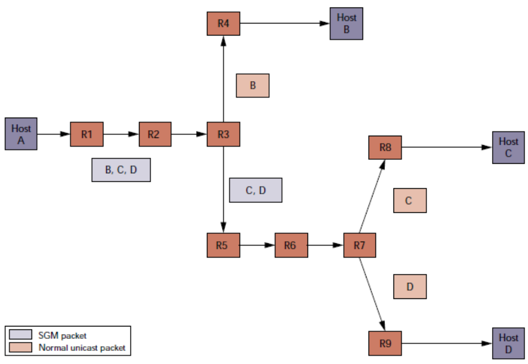

Figure 1: SGM Multicast Routing

Keeping this drawback in mind, Small Group Multicast (SGM)[2] protocol was developed as an alternative to IP Multicast. One key change in SGM is that it operates on top of IP protocols instead of operating along with the IP stack. As a result, SGM successfully lifts multicasting out of the IP network layer and introduces a stateless approach to multicast routing. The main difference between IP Multicast and SGM is that an SGM source node is aware of its receivers whereas an IP Multicast source node is completely blind about the data destination. The SGM source node keeps track of the destination nodes that it wants to send packets to. While sending a data packet, it encloses the address of each destination node in the SGM packet header that is forwarded to a router. The router then parses the header, partitions the destination set based on next hop destination and forwards SGM packets as appropriate. Finally, each end-junction removes SGM encoding and forwards packets as *unicast packet* to the destination as illustrated in figure 1.

Though SGM performs well in wired networks, it fails to achieve similar success in wireless networks because the destination partitioning in SGM is highly dependent on the nodes that are located at the branch-point of groups. Selection of such nodes is solely based on the shortest path but in wireless networks, particularly in MANETs, group formation needs to consider other factors such as availability of power amongst the participating nodes, their mobility and congestion of the network. Nevertheless, SGM remains the most noteworthy motivation of this proposed work and we will show later that a similar approach with a junction selection based on multiple constraints can significantly improve performance.

The second motivation of this work is Content-based network architecture that tries to separate content from host identity. We believe this approach is particularly appropriate for the scenarios where multiple nodes receive the same content because, in those scenarios, receivers are generally happy as long as they get the desired data and show little interest in knowing the exact provider. As a result, a node who is already a recipient of a particular data stream can easily become a sender for one of its neighbours interested in receiving the same data.

ROFL[3] is arguably one of the earliest proposals that established a network architecture independent of location. Instead of splitting identity from location, it removes the location altogether. To keep the design consistent in line with its goal, ROFL removes location addressing from the packet header and establishes a routing scheme based on identifiers (ID). This ID based network architecture gives enough flexibility to arrange and control content delivery without knowing the underlying host or its location; this is because in ROFL a physical box can have multiple IDs and an ID can be held by multiple physical boxes. However, ROFL is specially designed for wired networks and cannot be deployed directly in MANETs without major modifications to its core architecture.

DONA[4] is another clean-slate redesign, but for Internetworking. It particularly focuses on the shift from a host-centric to a data-centric network and works with a view to establish persistency, availability of data and services and authenticity. Unlike ROFL, DONA has a mechanism to operate in a mobile environment. However, the way it maintains mobile nodes is not suitable for MANETs. In DONA, a host with mobility can unregister itself from one location and re-register to a new location if required. In that case, associated information needs to be transferred to the new location along with the registration and, as soon as the new registration installs its necessary states, the operation resumes. But, there is a catch – it is difficult to achieve stability in a dynamic environment if registering and re-registering a host continuously.

A third architecture called CCN[5] is more suitable than ROFL and DONA. Its stated primary objective is to replace the term *where* (i.e. host) by *what* (i.e. content). It presents similar arguments to those of ROFL and DONA in favour of a content-based architecture instead of a host-oriented communication model. In general, CCN treats content as a primitive but unlike ROFL and DONA its architecture is not based on a proactive routing scheme. It has a more robust routing protocol and a TCP-like transport functionality to ensure reliability and maintain flow control. However, its major limitations are also hidden in those extra facilities. CCN routing is based on broadcast though this can be pruned via an ad hoc routing protocol, such as AODV, with necessary modifications. In addition, there is now a body of work that shows that TCP-like flow control and sequencing is not suitable in ad hoc networks.

There have been at least two more efforts [6, 7] that try to address these limitations of CCN in part but these did not demonstrate any mechanism for handling multiple constraints. As a result, none of those proposals can serve as a complete solution to the problem formulated above.

III. PROPOSED ARCHITECTURE

In this paper, we propose a fuzzy content centric network architecture for real-time communication in MANETs. Our work is motivated by SGM and CCN and we try to blend these two concepts together along with our fuzzy selection algorithm that handles multiple constraints while delivering real-time contents in groups. Before we present our design, we would like to explain some key terms that require clarification to have a better understanding of the architecture. In our design, the term *application* means a stream of real-time content such as audio, video, image or text being transmitted from a node. A node that transmits an application for the first time will be called *originating node*. Later, intermediate nodes depending on circumstances will take the responsibility of acting as the source for providing contents to the destination. Such nodes will be called *source nodes*. Nodes that receive content will be called *local nodes*.

A. Data Structure

In our proposed architecture each node maintains three data structures: a *node-to-application matrix* that keeps track of availability of application at each node; a *requested application list* that lists all the allocation requested by the local node; and a *suitability heap* that contains a special parameter called Ω for all source nodes associated with each request. This heap is a max-heap and rebuilds in *O(log n)* time. The purpose of having these data structures will be discussed later along with the discussion of the operation.

B. Selection Principle

In a content centric network, the presence of multiple nodes with same content generates a selection problem. For example, if four nodes in a MANET provide the same live football match, a local node would face a serious dilemma in selecting the most suitable source node. However, *suitability* of a node for becoming source of a specific local node depends on multiple constraints. A node having higher mobility is not suitable for performing the role of a source node because it may move away quickly. Similarly, a node located at a distance should be considered unsuitable. On the other hand, a congested node or a node running on low battery cannot be a suitable node even if it is relatively static and close to the local node. Therefore, we find four constraints in this problem – distance (*d*), congestion (*c*), mobility (*m*) and battery life i.e. power (*p*) – that must be addressed carefully. From the basis of these constraints, we designed and calculated a special parameter called Ω for each node using a fuzzy system and keep this parameter in the *suitability heap*. As mentioned earlier, this heap is a max-heap; therefore, it will be sorted in descending order based on the value of Ω. When a local node requests an application, it selects *root-node* as source from the heap. During transmission, this source node might move away or get congested or start running on low power. If any such change in its current state occurs, that will affect the value of Ω and eventually it will be pushed down in the suitability heap leaving the place for someone else to take over. Details of this operation will be discussed later.

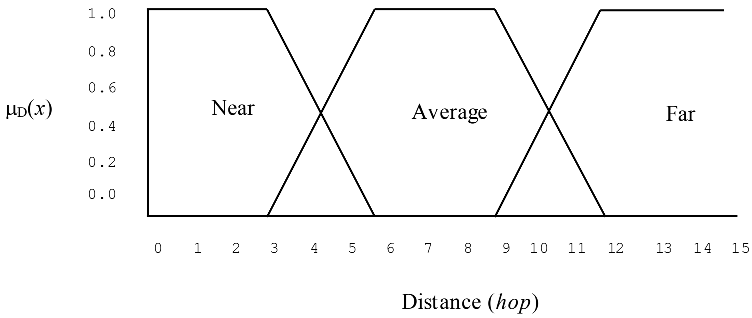

Figure 2: Membership function for $\mu_D(x)$

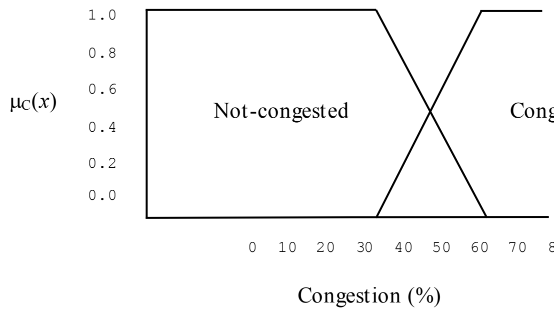

Figure 3: Membership function for $\mu_C(x)$

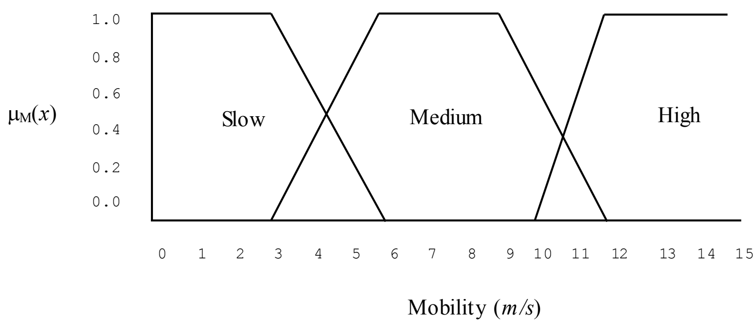

Figure 4: Membership function for $\mu_M(x)$

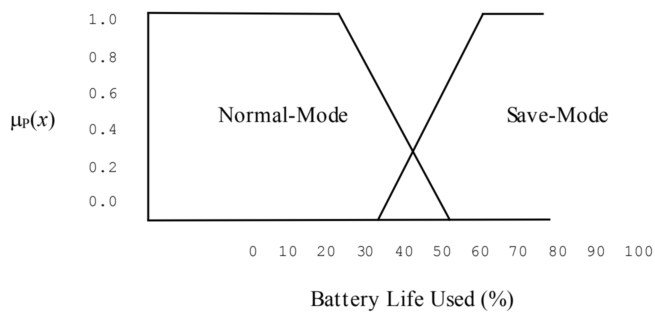

Figure 5: Membership function for $\mu_P(x)$

C. Calculation of Ω

We designed a fuzzy system[8] for calculating the value of Ω. In this system, we define distance as *near (N)*, *average (A)* and *far (F)* in terms of number of hops between nodes and congestion as *not-congested (NC)* and *congested (C)*. Membership functions for $\mu_D(x)$ and $\mu_C(x)$ are shown in figure 3 and 4 respectively. For the constraint mobility, we consider three situations namely *slow (S), medium (M)* and *high (H)* depending on node's velocity (m/s). Membership function for $\mu_M(x)$ is shown in figure 5. Finally, we define power in terms of two states, *normal-mode (NM)* and *safe-mode (SM)*. In our node selection, we discourage local nodes selecting a source node that is in safe-mode. Membership function for $\mu_P(x)$ is illustrated in figure 6.

This fuzzy system has seven rules described in equation 1 – 7. Each rule corresponds to seven possible states namely, extremely suitable (SE), very suitable (VE), suitable (S), neutral (N), unsuitable (U), very unsuitable (VU) and extremely unsuitable (EU).

$$\mu_{state=ES}(x) = \mu_{D=N}(x) \cap \mu_{C=NC}(x) \cap \mu_{M=L}(x) \cap \mu_{P=NM}(x) \quad (1)$$

$$\mu_{state=VS}(x) = \mu_{D=N}(x) \cap \mu_{C=NC}(x) \cap \mu_{M=M}(x) \cap \mu_{P=NM}(x) \quad (2)$$

$$\mu_{state=S}(x) = \mu_{D=A}(x) \cap \mu_{C=NC}(x) \cap \mu_{M=M}(x) \cap \mu_{P=NM}(x) \quad (3)$$

$$\mu_{state=N}(x) = \mu_{D=A}(x) \cap \mu_{C=C}(x) \cap \mu_{M=M}(x) \cap \mu_{P=NM}(x) \quad (4)$$

$$\mu_{state=U}(x) = \mu_{D=A}(x) \cap \mu_{C=C}(x) \cap \mu_{M=H}(x) \cap \mu_{P=NM}(x) \quad (5)$$

$$\mu_{state=VU}(x) = \mu_{D=F}(x) \cap \mu_{C=C}(x) \cap \mu_{M=H}(x) \cap \mu_{P=NM}(x) \quad (6)$$

$$\mu_{state=EU}(x) = \mu_{D=F}(x) \cap \mu_{C=C}(x) \cap \mu_{M=H}(x) \cap \mu_{P=SM}(x) \quad (7)$$

We applied the *Centroid Defuzzification Technique* that provides us with Ω as shown in equation 8.

$$\Omega = \frac{\int \mu_{output}(x)xdx}{\int \mu_{output}(x)dx} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

IV. Operation

Our proposed architecture has a reactive operation strategy with greedy-choice selection approach. When a local node receives a request from its user to find an application, it triggers our modified version of the AODV[7] protocol called Content Centric-AODV or simply CC-AODV. This version of AODV sends a Route Request (RREQ) for a specific content instead of a specific IP address. In turn, if multiple copies of the requested content are found in the network, CC-AODV receives multiple Route Replies (RREPs). Each RREP packet contains the value of *d*, *c*, *m* and *p* for the respective nodes. Once a local node receives RREP packets, it calculates Ω using the method described earlier and inserts each node in the *suitability-heap*. Then it picks the root-node as its source. However, during content transmission, we always insert the *d*, *c*, *m* and *p* of the source node in the data packet. This helps to keep track whether or not a change is occurring in the network regarding the source node. If any negative change occurs, that will push the source node down in the suitability-heap. The local node then picks the new root-node and sends a *hello-packet* to ascertain its current status. In response, that node replies with its *d*, *c*, *m* and *p*. If the local node still finds this node suitable enough to become its new source node, it requests a *hand-off*. Note that a *hand-off*, in our architecture, is a process of simply informing previous source node to stop sending data and new source node to start sending data.

When a local node receives real-time content from its source node, it can start acting as a source node for other neighboring nodes by buffering data for a certain period. However, neighboring nodes that follow this node as the source node will be completely unaware of any *hand-off* process involving this local node and its source nodes.

It is evident from the description of the operation that the proposed architecture provides us with two great benefits: firstly, it drastically decreases number of hops between originating nodes and local nodes by introducing intermediate source nodes; and secondly, it presents a flexible group management technique especially designed for MANETs.

V. Evaluation and Results

We have used a custom packet-based simulator implemented in C++ to evaluate and compare the performance of our proposed architecture. In this section, we will call it the Fuzzy Content Centric Network (FCCN) and evaluate against UDP/IP.

We conducted three sets of experiments with 21 nodes for observing the number of packets being transferred between end-nodes. We decided to use a custom-built simulator because the objective of our experiment was not to analyze propagation delay or any network parameter but rather to observe number of packets required for distributing certain contents. A C++ based multi-threading simulation is an efficient and quicker way to generate this environment.

The results of the first experiment in figure 7 demonstrate the performance of individual transmissions. In order to show this we randomly pick one node as the originating node and then select local nodes one by one – up to six – which want to receive content from it. For each segment (a small chunk of the original content), we then determine τ, the number of hops a packet needs to travel to reach its destination. For example, to transfer a segment over a five-hop path, 5τ effort is required.

Results show that initially when only one node receives contents, τ for FCCN and UDP/IP were the same. However, as the number of nodes increased, the relative performance of FCCN is enhanced, i.e. it requires less effort to transfer contents to local nodes compared to UDP/IP. The reason behind this improvement is that the architecture of FCCN automatically establishes a group-based communication model that shares content instead of fetching it every time from the originating node.

Result shows that FCCN performed better than UDP/IP and when all nodes were in active mode, the effort FCCN required for distributing content among group members was half of that required by UDP/IP.

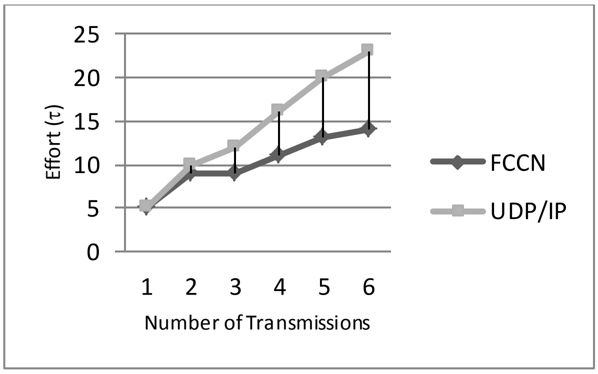

Figure 7: Performance of Individual Transmissions

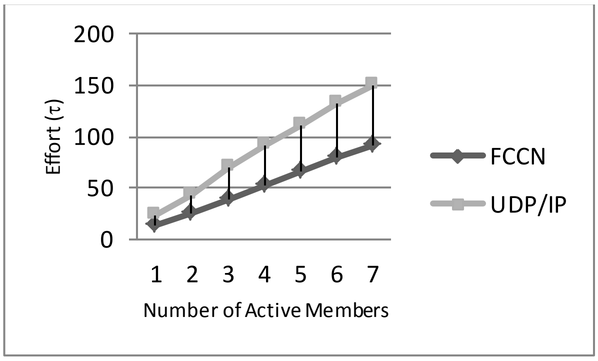

Figure 8: Performance of Conference Communications

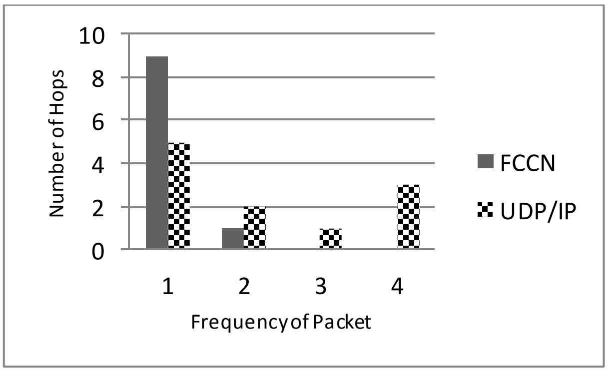

Figure 9: Frequency of Packets on Hops

Our second experiment with results showed in figure 8 exhibits the performance of conference communications. This time we select a random node communicating with 7 other members. However, initially we place all member nodes in listening mode, i.e. one originating node and all other local nodes but gradually everyone becomes an active participant, i.e. receiving content from each node and delivering content to each node.

The results of the third experiment, presented in figure 9, demonstrate the frequency of packets on hops. We randomly pick one originating node and six local nodes that receive contents from it. Then for each hop we count the number of packets sent to deliver the same segment to the local nodes. The result shows that UDP/IP used same communication path to send same content multiple times. On the other hand, FCCN is much more efficient in distributing contents to all members using same communication paths the minimum number of times.

VI. Conclusion and Future Work

In this paper we propose a fuzzy content centric network architecture and, using simulated experiments, show that it performs better than the existing IP stack. Though the design of this architecture focuses on emergency and tactical MANETs dealing with real-time data, it is also possible to extend this design to a general purpose network with minimum modification, an endeavor that we consider as a future work. Our future work also aims to use this concept for distributing warning message amongst cars in Vehicular Ad-hoc Networks (VANETs).

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