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Optimized Group Owner Selection in WiFi Direct Networks

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Abstract—**Device-to-Device communication is an essential component in the evolution towards the Internet of Things. The relatively new WiFi-Direct standard allows devices to communicate directly over the well established IEEE 802.11 protocol without the need for an intermediate access point. The increased range and bandwidth advantage of WiFi-Direct over existing short-range technologies such as Bluetooth and Zigbee allows a whole new class of applications to benefit from cooperation. Within a WiFi-Direct network, one device is elected as the group owner and acts as a central hub for all communications. The standard does not dictate a group owner selection strategy and leaves the decision to be taken at the application layer. In this work, we present an optimized strategy for group owner selection within WiFi-Direct networks that aims at maximizing the overall network performance in terms of increased throughput. Moreover, we propose a low complexity multi-device group owner negotiation protocol that runs at the application layer and extends the existing WiFi-Direct protocol, which limits group owner negotiation to two devices only. Simulation results demonstrate the effectiveness of the proposed selection strategy in achieving near-optimum results.**

I. INTRODUCTION

With the increasing demand on wireless cellular and local area networks, there is increased interest in supporting device-to-device (D2D) communications for a wide range of data sharing mobile applications. Direct short-range wireless connectivity among mobile devices has already been proven to be a key performance enhancement solution, e.g., for cellular traffic offloading [1] [2], large-scale multimedia distribution [3], and emergency broadcast through opportunistic networks [4].

The need for infrastructure-less communication between devices is not new. In fact, the original WiFi specification supported an *ad hoc* mode (IBSS), allowing two devices to communicate directly without an intermediate access point. This mode, however, never got widely adopted nor matured enough to support novel and essential features such as power saving and QoS capabilities. Another take at direct WiFi device-to-device communication is the Direct Link Setup (DLS) as introduced in IEEE 802.11z [5]. While DLS was considered an improvement over the ad hoc mode, it still required that the devices be associated with the same access point to setup the direct communication link, limiting its use cases. WiFi-Direct, on the other hand, took a completely different approach to D2D communications. WiFi-Direct builds on the very successful *infrastructure* mode in IEEE 802.11 and, thus, inherits all the benefits of the protocol developed over the years [6]. WiFi-Direct basically is an extension that allows a device to assume the role of the access point and, hence, offer other nearby devices with an on-demand infrastructure for communication.

Traditional short-range wireless technologies such as Bluetooth Low Energy (BLE) and ZigBee, while still being popular, offer limited coverage range and bandwidth capability. WiFi-Direct allows for wider coverage at around ten times the bandwidth offered by BLE. This paves the way for a multitude of applications in diverse areas ranging from health care, vehicular networks, to smart cities.

Within a WiFi-Direct network (referred to as group), one device is designated as the group owner and serves as a focal point of communication among all devices. The group owner will assume the role of an access point and act as a relay to all communications between nearby devices in the group. The WiFi-Direct protocol currently allows for group owner negotiation between two devices. During the negotiation, each device will express its willingness to act as the group owner through a numerical value known as the intent value. The device with the highest intent value is then chosen as the group owner. This value is naturally application specific and is left to the application designers to determine.

Clearly the group owner choice is a major decision that could either positively or negatively affect the quality of service for all nodes within the group. Few works in the literature can be found that tackle optimal group owner selection in a multi-device WiFi-Direct network. In [7], the authors suggest selecting the group owner with the best average RSSI from all other devices in the group; they claimed a 45% improvement in the total network throughput using their approach. Our experiments, however, show that the average RSSI strategy will not perform well on large groups. In [8], the authors present a strategy for dynamic clustering of devices in WiFi-Direct networks; their algorithm depends heavily on parameters that might prove hard to obtain in practice such as the relative location of the devices.

In this work, we propose a new strategy for group owner selection that aims at maximizing the total throughput within the group. Moreover, given that the standard only supports group owner negotiation between two devices, we present a way that leverages the service discovery feature of WiFi-

Direct to implement any multi-device group election algorithm entirely at the application level.

The rest of this paper is organized as follows: in Section II, we present our system model and give an overview of the WiFi-Direct group formation protocol along with its limitations. In Section III, we propose our group owner selection strategy and show how it can be implemented entirely at the application layer. We present simulations results with detailed analysis in Section IV. Finally, conclusions are drawn in V.

II. SYSTEM MODEL

Unlike other D2D wireless technologies that typically implement a mesh topology, WiFi-Direct (WD) follows a client/server architecture. In this architecture, the mobile devices communicate by first establishing a WD group. Within a group, a single device is elected as the Group Owner (GO) while other devices are designated as clients. These roles within a WD group are purely logical. Thus, it is possible for a device to assume the role of GO in one group while being a client device in another group. This is possible, as long as the device is equipped with multiple interfaces or implements time-sharing. Figure 1 shows an example WiFi-Direct group between five devices.

All communication within a WD group must pass through the GO. To realize this, a GO implements standard IEEE 802.11 access point (AP) functionality (sometimes referred to as soft-AP), among other services to support, for instance, addressing (DHCP server) and bridging to external networks (NAT). This also allows legacy devices to effortlessly connect to an existing WD group.

A. WiFi-Direct Group Formation Overview

The WiFi-Direct standard essentially adds two pieces to the existing WiFi protocol: a discovery and group formation algorithm and a power saving mechanism for the group owners. The latter is out of the scope of this paper. Next, we describe how a WD group is established. The group formation algorithm is divided into two phases: a *Scan* phase, followed by a *Find* phase. During the *Scan* phase, the devices will perform a traditional WiFi scan to discover nearby access points and existing WD groups. The *Find* phase is executed next. First, a device will select one of the pre-defined "*Social*" channels (1, 6, and 11 in the 2.4 GHz band) as its listen channel. Then, the device alternates between a *Listen* state and a *Search* state. In the *Search* state, a device sends *Probe Requests* on all the *Social* channels, while in the *Listen* state, a device listens for incoming *Probe Requests* on its selected *Social* channel and reply with *Probe Responses*. To facilitate convergence, the amount of time a device spends in each state is chosen randomly.

Once two devices discover each other, they begin the negotiation phase to agree on a GO and the channel that the group will operate on. The device that initiates the connection first sends a *Negotiation Request* that includes, among other parameters, *Intent Value* (IV) and a tie-breaking bit. The IV is a numerical value between 0 and 15 that indicates the willingness of the device to act as a GO. The standard does not dictate a specific way to compute the IV, except that it should reflect the device's capabilities. The tie-breaking bit is set randomly. When the other device receives the *Negotiation Request*, it will respond with a *Negotiation Response* that includes its own IV and with the tie-breaking bit negated. This process is concluded with a *Negotiation Confirmation* message. The device with the highest IV will then act as the GO. In case both devices' IV matched, the device with the tie-breaking bit set will act as GO. Finally, the GO will launch its soft-AP and DHCP server and the client device can connect to the group, typically via WiFi Protected Setup (WPS).

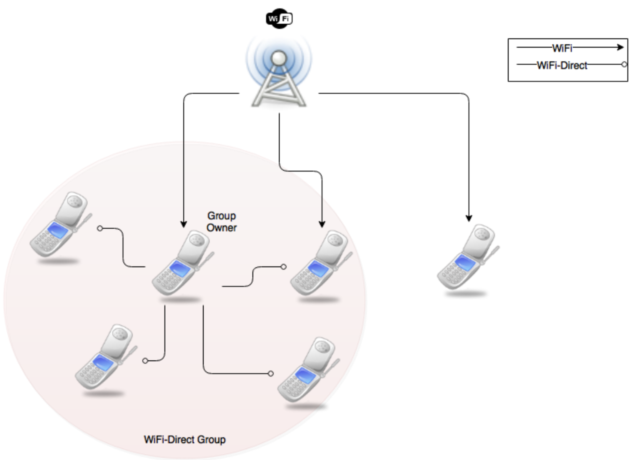


Fig. 1. Example system model

The standard also defines two other ways for a device to join a group where the whole negotiation phase is skipped. In *Autonomous* mode, a device can self-declare itself as a GO and launch a WD group. In this case, a client device just connects to the existing group owner. This is also the case when a group between two devices is formed using the process described earlier and a third device wishes to join the group. The other mode is the *Persistent* mode that is useful to quickly re-instantiate a previous WD group formation saved on the device.

B. Challenges and Problem Description

The WiFi-Direct standard defines a clear procedure for group formation between two devices. However, it is ambiguous when it comes to establishing a group between multiple devices. In fact, the algorithm presented can only correctly handle group formation for a maximum of two devices. Practical implementations often fail at establishing groups with a larger number of devices or they do it in succession [9], meaning that the group owner is decided between the first two devices that initiate the connection while others just connect to the selected owner in autonomous mode. Clearly, this is not an optimal group owner selection strategy.

Another challenge is the group formation time. The authors in [9] showed that, at least for the Android implementation, the group formation time when four devices are involved can range from 86.5 to 275 seconds. For many applications where the contact-time between devices is short (for instance, vehicular networks), this delay is intolerable. Moreover, the standard dictates that the group owner shall remain fixed for the entire group lifetime. If the group owner leaves, the group would be disconnected. Many real-life applications are in highly dynamic environments where devices may join or leave the network quickly. The authors in [10] attempted to remedy this problem by introducing an *Emergency Intent Value* to the protocol where each device expresses its willingness to act as a backup group owner.

The intent value is typically left for the application to determine. This makes sense since in some applications, for instance, a specific device may be required to be the group owner. In this case, the application can simply set the intent value of that device to 15 prior to making the connection. Since all communications must pass through the group owner, in many applications it is often desired that the group owner is selected in a way that maximizes the total throughput. Here, it is up to the application to calculate and set the intent value accordingly. If not set, then the group owner is assigned randomly according to the tie-breaking bit and the assignment may not be optimal. In this paper, we tackle specifically this problem: given a set of WiFi-Direct devices, how can we select a group owner in practice to optimize the overall network throughput in compliance with WiFi-Direct specifications?

III. PROPOSED GROUP OWNER NEGOTIATION AND SELECTION STRATEGY

As mentioned earlier, the WiFi-Direct standard group formation protocol is limited to two devices. The intent value and the tie-breaking bit are exchanged between two devices only and one of them is ought to be the group owner. All other devices are not considered for group ownership and they only associate with the group owner after it is determined. One major feature specified by the WiFi-Direct protocol is the ability for WD devices to query each other for available services prior to group formation. This allows a device to discover services offered by nearby devices, and to connect to a specific device only if it offers some service of interest. This feature is implemented using the Generic Advertisement Protocol (GAS) specified by IEEE 802.11u that allows the transport of higher-layer protocols (such as UPnP or Bonjour) at the link layer. Next, we show how we can leverage service discovery through a simple procedure to implement any multi-node group owner negotiation protocol that is based on the exchange of intent values entirely at the application layer.

After the discovery phase and upon computing the intent value, none of the devices will attempt to connect to one another. Instead, each device will announce a WiFi-Direct service using some predefined service identifier containing its intent value as a payload. Each device would then query its neighbors for available services and extract their intent values. At this stage, each device knows the intent value of all of its neighbors. Next, each device will independently compute the maximum intent value among the values received. If the maximum happened to match the device's local intent value, the device would start a WiFi-Direct group in autonomous mode. Otherwise, a device simply waits for the device with the maximum intent value to start the group (by repeatedly scanning for access points) and then simply connect to the group.

RSSI Level	**Min P_r**	**Max P_r**	**Description**
0	$-\infty$	-81	Very bad signal
1	-81	-78	Bad signal
2	-78	-73	Average signal
3	-73	-65	Good signal
4	-65	0	Excellent signal

TABLE I
RECEIVED POWER (P_r) TO QUANTIZED $RSSI$ LEVEL MAPPING

It might happen that multiple devices have the same maximum weight. A device with maximum weight will only start a WD group if and only if its MAC address is smallest lexicography among all devices that share the same weight. Note that the maximum weight a device computes might be local to its neighborhood and not the absolute global maximum. In this case, the selected group owner is not in range of the device anyway and it can never join the group.

Given that the group owner in a WiFi-Direct is central to all communications within the group, we aim at selecting a group owner that maximizes the bit rate between the selected GO and every other device in the group. One of the very few quality metrics that can be collected in practice during the device discovery phase is the power received (P_r) from nearby WD devices, which gives an indicator of the the received signal strength (RSSI) level between the two devices.

In our algorithm, each device starts by running a standard WD device discovery procedure and collecting received signal strength level for every discovered device, which is then mapped to a quantized RSSI level based on the mapping given in Table III. The mapping classifies the discovered devices into five categories depending on the quality of the signal received. Then, each device calculate its own weight as follows:

$$w = \frac{\prod_{i=1}^{n} RSSI(i)}{n} \tag{1}$$

where $RSSI(i)$ is the quantized RSSI level of device i and n is the number of discovered devices. Note that devices with $RSSI = 0$ are excluded from the computation as they are considered out of range. Finally, the weight is mapped into a valid WD intent value as follows:

$$IV = \frac{15}{4(n-1)-1}(w-1) \tag{2}$$

IV. PERFORMANCE RESULTS AND ANALYSIS

We evaluate our algorithm, denoted *MutualRSSI*, against two other algorithms: *Random*, where the group owner is chosen randomly, and *AverageRSSI*, where the device with the highest average RSSI from all other devices is picked as the

Bitrate	**Min** SNR	**Max** SNR
0	0	4
6	4	5
9	5	7
12	7	9
18	9	12
24	12	16
36	16	20
48	20	21
54	21	∞

TABLE II
SNR IN dB TO BIT RATE IN MBPS MAPPING

group owner; in other words, the weight of each device in the *AverageRSSI* algorithm is calculated as follows:

$$w = \frac{\sum_{i=1}^{n} RSSI(i)}{n}$$

This approach is similar to the one described in [7].

The simulation starts by randomly scattering between 2 and 256 devices in $15m \times 15m$ two-dimensional Cartesian plane. Let $d(i, j)$ be the Euclidean distance between devices i and j. Then, the power received between devices i and j is calculated as follows:

$$P_r = \kappa \left(\frac{d_0}{d(i,j)} \right)^{\mu} P_t$$

where κ, μ, d_0, P_t are pathloss constant, pathloss exponent, reference distance (typically set to 1 m), and transmit power, respectively. The received power in dBm is is then used with Table III to determine the corresponding RSSI level.

For any given WD group with device i as the group owner, we evaluate the bit rate at each client device by first calculating the Signal-to-Noise Ratio (SNR) as follows:

$$SNR = \frac{P_r}{\sigma^2}$$

where σ is the thermal noise variance. Finally, we use Table IV to map the SNR in dB to a corresponding bit rate value based on the different supported adaptive modulation and coding schemes in the standard.

Figure 2 shows four scenarios generated using our simulator. Each node represents one device and the label above each node indicates the average bit rate per-node if that node was selected as the group owner. In all scenarios, the *MutualRSSI* algorithm picked a group owner that leads to near-optimal bit rate performance. This snapshot example demonstrates the effectiveness of the proposed approach.

We recorded the bit rate on each device over 10,000 runs each time using both the *MutualRSSI* group owner selection strategy, and the random selection of the group owner. As shown in Figure 3, with both 8 devices and 32 devices in the group, using the *MutualRSSI* algorithm for GO selection always led to a higher average bit rate per device than the random selection strategy. Likewise, Figure 4 shows that more devices had higher bit rate when following the *MutualRSSI* strategy.

In Figure 5, we compare our algorithm against the optimal GO selection and the $AverageRSSI$ selection algorithm for

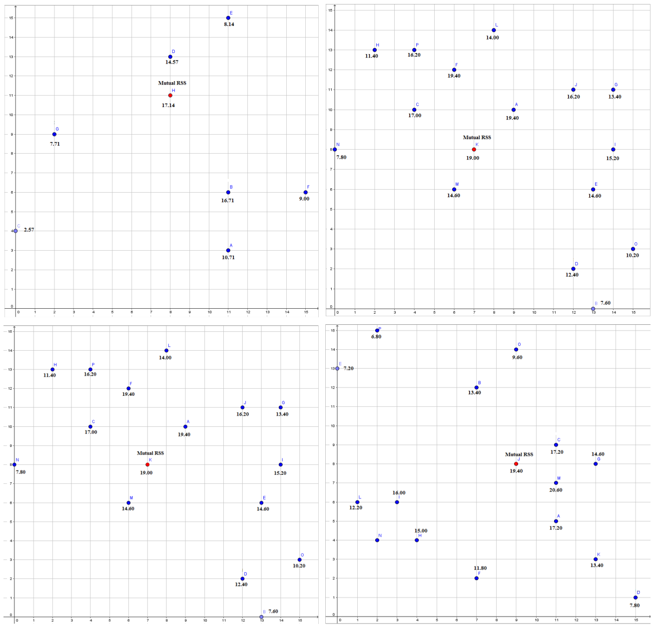
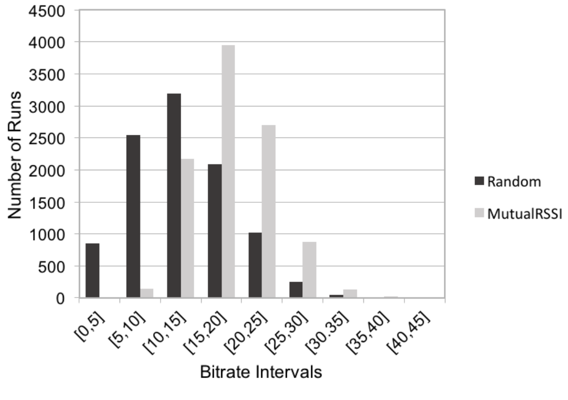
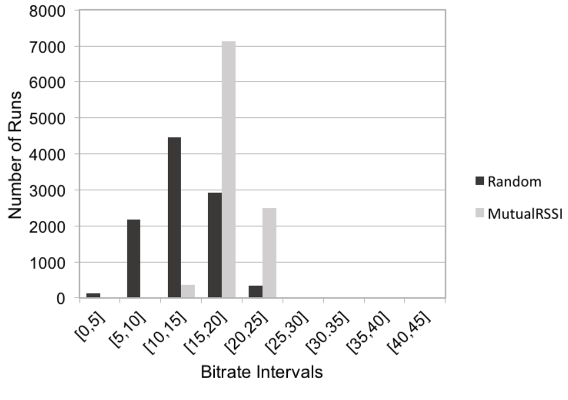


Fig. 2. The average bit rate per-node for every possible group owner selection for four generated scenarios. In all scenarios, the *MutualRSSI* algorithm managed to pick the group owner that leads to a near-optimum bit rate (shown in red).

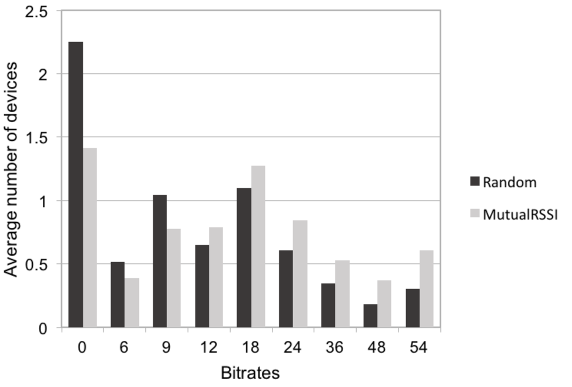


(a) 8 devices

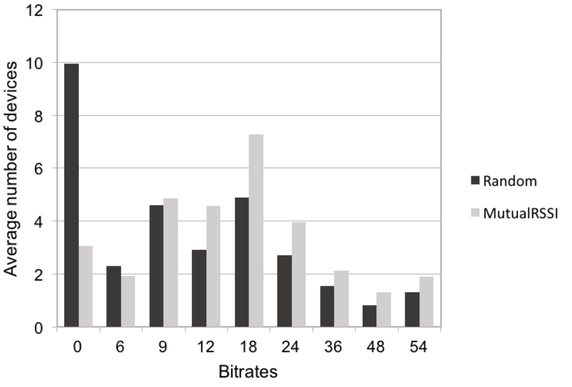


(b) 32 devices

Fig. 3. The average per-device bit rate distribution over 10,000 runs using the *MutualRSSI* algorithm vs. random GO selection.



(a) 8 devices



(b) 32 devices

Fig. 4. The bit rate distribution among the devices using the *MutualRSSI* algorithm vs. random GO selection.

groups with two devices up to 256 devices. For each group size, we ran 10,000 different scenarios each time recording the average bit rate per device. Figure 5 shows the average of those runs. The optimum is calculated using a brute force approach by trying to assign each device in the group as group owner and calculating the resulting average rate, then choosing the case that leads to maximum throughput. Figure 5 shows that, unlike the *AverageRSSI* algorithm, the *MutualRSSI* algorithm converged towards the optimum rate as we increased the number of devices. The steady decline in the *AverageRSSI* algorithm is most likely due to the increased number of outliers as we increase the number of devices.

V. CONCLUSION

We presented a group owner selection strategy for WiFi-Direct networks that aims at maximizing the bit rate for all devices within the group. Our experiments showed that as we increased the number of devices, the average per-device bit rate converged towards the optimum. We have shown how we can practically implement our approach entirely at the application layer without any modifications to the WiFi-Direct protocol by leveraging the existing WiFi-Direct service discovery feature. Future work includes extending our framework to include additional parameters for group owner selection by taking into account other variables that reflects the devices' capabilities. Such parameters include but are not limited to the CPU frequency and battery lifetime. Moreover, this work targets scenarios where all the devices are interested in forming a single WiFi-Direct group. We would like to further explore the possibility of clustering the target devices into multiple groups especially since the standard allows a single WiFi-Direct device to belong to multiple groups.

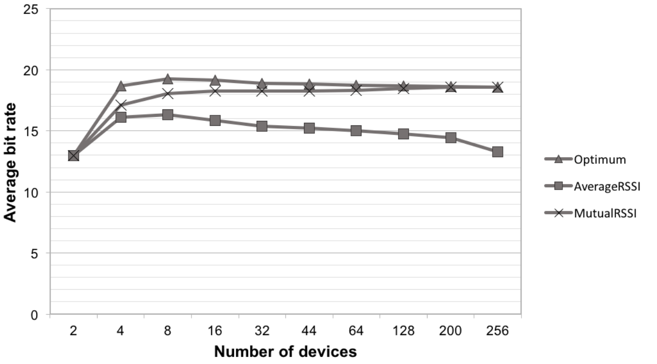


Fig. 5. The average total network bit rate using the *MutualRSSI* algorithm vs. the *AverageRSSI* algorithm and optimum selection.

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